Duality theory of \( p \)-adic Hopf algebras

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Abstract. We show the monoidal functoriality of Schikhof duality, and cultivate new duality theory of \( p \)-adic Hopf algebras. Through the duality, we introduce two sorts of \( p \)-adic Pontryagin dualities. One is a duality between discrete Abelian groups and affine formal group schemes of specific type, and the other one is a duality between profinite Abelian groups and analytic groups of specific type. We extend Amice transform to a \( p \)-adic Fourier transform compatible with the second \( p \)-adic Pontryagin duality. As applications, we give explicit presentations of a universal family of irreducible \( p \)-adic unitary Banach representations of the open unit disc of the general linear group and its \( q \)-deformation in the case of dimension 2.

1 Introduction

Let \( k \) be a non-Archimedean local field. We denote by \( O_k \) its valuation ring, and by \( p \) the characteristic of the residue field of \( O_k \). As a \( p \)-adic analogue of the reflexivity of Hilbert spaces, Schikhof duality (cf. [6] Theorem 4.6) gives a contravariant categorical equivalence between Banach \( k \)-vector spaces and localisations of compact Hausdorff flat linear topological \( O_k \)-modules. We
show the monoidal functoriality of Schikhof duality in Theorem 3.2, and study a new duality between Hopf monoid objects in Theorem 3.6.

Through the duality restricted to commutative cocommutative Hopf monoid objects, we introduce two sorts of $p$-adic Pontryagin dualities. One is a contravariant categorical equivalence between discrete Abelian groups (discrete side) and affine formal group schemes over $O_k$ of specific type (compact side), and the other one is a contravariant categorical equivalence between profinite Abelian groups (compact side) and analytic groups over $k$ of specific type (discrete side). Therefore they are variants of the duality between compactness and discreteness.

We explain the relation with classical results. Iwasawa isomorphism is a well-known isomorphism between the Iwasawa algebra $O_k[[\mathbb{Z}_p]]$ and the formal power series algebra $O_k[[T]]$, which represents the affine formal group scheme $U_1/O_k$ given as the completion of the multiplicative group scheme $\mathbb{G}_m/O_k$. Through the identification of $O_k[[\mathbb{Z}_p]]$ and the continuous dual of the continuous function algebra $C(\mathbb{Z}_p, k)$, it gives an isomorphism called Amice transform from the continuous dual of $C(\mathbb{Z}_p, k)$ to the algebra of global sections on $U_1/O_k$. Therefore Amice transform gives a non-trivial connection between functions on the profinite Abelian group $\mathbb{Z}_p$ and the affine formal group scheme $U_1/O_k$. In addition, the second $p$-adic Pontryagin duality sends $\mathbb{Z}_p$ to $U_1/O_k$, and hence Amice transform can be regarded as a $p$-adic analogue of Fourier transform for the specific dual pair $(\mathbb{Z}_p, U_1/O_k)$. The duality between Hopf monoid objects yields a Hopf monoid isomorphism in a wider case in Theorem 4.23, and hence can be regarded as a $p$-adic analogue of Fourier transform extending Amice transform.

The notion of a representation of an affine formal group scheme $\mathcal{G}$ of specific type can be formulated in terms of a comodule object. Through the duality between Hopf monoid objects, it can be naturally identified with the notion of a module object over the dual Hopf monoid $A$ of the coordinate ring of $\mathcal{G}$. By the functoriality of $\mathcal{G}$, every $A$-module object can be regarded as a unitary Banach $k$-linear representation of the discrete group $\mathcal{G}(O_k)$. Then the regular $A$-module can be regarded as a universal family of irreducible unitary Banach $k$-linear representations of $\mathcal{G}(O_k)$ which can be obtained in this way.

As applications of the duality between Hopf monoid objects, we give explicit presentations of the universal family of irreducible unitary Banach $k$-
linear representations of the open unit disc, that is, the discrete group of the
$O_k$-valued points of the affine formal group scheme given as the completion,
of the general linear group and a $q$-deformation of the universal family in
the case of dimension 2.

We explain contents of this paper. First, §2 consists of two subsections. In
§2.1, we recall compact Hausdorff flat linear topological $O_k$-modules. In
§2.2, we recall Banach $k$-vector spaces. Secondly, §3 consists of two subsec-
tions. In §3.1, we show the monoidal functoriality of Schikhof duality. In
§3.2, we study the associated duality between Hopf monoid objects. Thirdly,
§4, consists of three subsections. In §4.1, we investigate the $p$-adic Pon-
tryagin duality between discrete Abelian groups and affine formal groups
schemes over $O_k$ of specific type. In §4.2, we investigate the $p$-adic Pon-
tryagin duality between profinite Abelian groups and analytic groups over
$k$ of specific type. In §4.3, we study the $p$-adic Fourier transform. Finally,
§5 consists of two subsections. In 5.1, we give an explicit description of
the universal family of irreducible unitary Banach $k$-linear representations
of the open unit disc of the general linear group. In 5.2, we give a similar
description of a $q$-deformation of the universal family.

2 Preliminaries

We fix a Grothendieck universe $\mathcal{U}$ in order to avoid set-theoretic problems.
A set $x$ is said to be $\mathcal{U}$-small if $x \in \mathcal{U}$. Throughout this paper, let $k$ denote
a fixed $\mathcal{U}$-small local field, that is, a complete discrete valuation field with
finite residue field, $O_k \subset k$ the valuation ring of $k$, and $p$ the characteristic
of the residue field of $O_k$.

We introduce the convention and the terminology for categories, which
is always assumed to be small but is not assumed to be $\mathcal{U}$-small. We de-
note by $\mathcal{C}$ (respectively, $\mathcal{C}_k$) the Abelian category of $\mathcal{U}$-small $O_k$-modules
(respectively, $k$-vector spaces) and $O_k$-linear homomorphisms. Then the tri-
ads $(\mathcal{C}, \otimes_{O_k}, O_k)$ and $(\mathcal{C}_k, \otimes_k, k)$ form symmetric monoidal categories. The
correspondence $M \sim k \otimes_{O_k} M$ restricted to $\mathcal{U}$ gives a symmetric monoidal
functor $(\mathcal{C}, \otimes_{O_k}, O_k) \to (\mathcal{C}_k, \otimes_k, k)$. We abbreviate “$(\mathcal{C}, \otimes_{O_k}, O_k)$-enriched”
(respectively, “$(\mathcal{C}_k, \otimes_k, k)$-enriched”) to “$O_k$-linear” (respectively, “$k$-linear”).
For an $O_k$-linear category $\Theta$, we denote by $k\Theta$ the $k$-linear category obtained
as the localisation of $\Theta$ by the symmetric monoidal functor $(\mathcal{C}, \otimes_{O_k}, O_k) \to$
(\mathcal{C}_k, \otimes_k, k). For an \( O_k \)-linear functor \( \Phi \), we denote by \( k\Phi \) the \( k \)-linear extension of \( \Phi \).

We denote by Set the category of \( \mathcal{U} \)-small sets and maps, by Top the category of \( \mathcal{U} \)-small topological spaces and continuous maps, by PTop \( \subset \) Top the full subcategory of \( \mathcal{U} \)-small totally disconnected compact Hausdorff topological spaces, by Grp the category of \( \mathcal{U} \)-small discrete groups and group homomorphisms, by Ab \( \subset \) Grp the full subcategory of \( \mathcal{U} \)-small discrete Abelian groups, by PGrp the category of \( \mathcal{U} \)-small profinite groups and continuous group homomorphisms, and by PAb \( \subset \) PGrp the full subcategory of \( \mathcal{U} \)-small profinite Abelian groups. For topological spaces \( X \) and \( Y \), we denote by \( C(X, Y) \) the set of continuous maps \( X \to Y \).

### 2.1 Topological module

A **topological \( O_k \)-module** is an \( O_k \)-module \( M \) equipped with a topology for which the addition \( M \times M \to M \) and the scalar multiplication \( O_k \times M \to M \) are continuous. We denote by \( \mathcal{O}(M) \) the set of open \( O_k \)-submodules of \( M \). We say that \( M \) is **linear** if \( \mathcal{O}(M) \) forms a fundamental system of neighbourhoods of \( 0 \in M \), is **flat** if its underlying \( O_k \)-module is flat, and is **compact Hausdorff** if its underlying topological space is compact and Hausdorff.

**Example 2.1.** Let \( I \) be a set, and \( M \) a topological \( O_k \)-module, e.g. \( O_k \). We denote by \( M^I \) the direct product of \( I \)-copies of the underlying \( O_k \)-module of \( M \) equipped with the direct product topology. Then \( M^I \) forms a topological \( O_k \)-module. If \( M \) is compact (respectively, Hausdorff, flat, linear), then so is \( M^I \).

Let \( M_0 \) and \( M_1 \) be compact Hausdorff linear topological \( O_k \)-modules. For each \((L_0, L_1) \in \mathcal{O}(M_0) \times \mathcal{O}(M_1)\), we equip \( M_0/L_0 \otimes O_k M_1/L_1 \) with the discrete topology so that it again forms a compact Hausdorff linear topological \( O_k \)-module by the finiteness of its underlying set. We denote by \( M_0 \hat{\otimes} O_k M_1 \) the inverse limit of \((M_0/L_0 \otimes O_k M_1/L_1)_{(L_0, L_1)} \in \mathcal{O}(M_0) \times \mathcal{O}(M_1)\) with respect to canonical projections equipped with the inverse limit topology. We give an explicit example of the completed tensor product.

**Proposition 2.2.** Let \( I_0 \) and \( I_1 \) be sets. Then there is a natural homeomorphic \( O_k \)-linear isomorphism \( O_k^{I_0} \otimes O_k^{I_1} \to O_k^{I_0} \hat{\otimes} O_k^{I_1} \).

**Proof.** Let \((L_0, L_1) \in \mathcal{O}(O_k^{I_0}) \times \mathcal{O}(O_k^{I_1})\). Put \( M_{L_0, L_1} := O_k^{I_0}/L_0 \otimes O_k^{I_1}/L_1 \). Let \( h \in \{0, 1\} \). For each \( i \in I_h \), we denote by \( \delta_{I_h, i} \in O_k^{I_h} \) the characteristic
function of \( \{i\} \subset I_h \). By the definition of the direct product topology, there is a finite subset \( J_h \subset I_h \) such that \( \{(m_i)_{i\in I_h} \in O_k^{I_h} \mid \forall i \in J_h, m_i = 0\} \subset L_h \). We denote by \( f_{L_0,L_1} \) the composite of the canonical projection \( O_k^{I_0\times I_1} \twoheadrightarrow O_k^{I_0\times J_1} \) and the following \( O_k \)-linear homomorphism, which is continuous by the continuity of the \( O_k \)-module structure of \( M_{L_0,L_1} \):

\[
O_k^{I_0\times J_1} \to M_{L_0,L_1} \quad (c_{i_0,i_1})_{(i_0,i_1)\in I_0\times J_1} \mapsto \sum_{(i_0,i_1)\in I_0\times J_1} c_{i_0,i_1} (\delta_{i_0,i_0} + L_0) \otimes (\delta_{i_1,i_1} + L_1)
\]

Then \( f_{L_0,L_1} \) is independent of the choice of \( (J_0,J_1) \) by \( (\delta_{i_0,i_0} + L_0) \otimes (\delta_{i_1,i_1} + L_1) = 0 \in M_{L_0,L_1} \) for any \( (i_0,i_1) \in (I_0 \setminus J_0) \times (I_1 \setminus J_1) \), and is surjective because \( \{(\delta_{i_0,i_0} + L_0) \otimes (\delta_{i_1,i_1} + L_1) \mid (i_0,i_1) \in I_0 \times I_1\} \) generates \( M_{L_0,L_1} \).

By the definition, \( (f_{L_0,L_1})_{(L_0,L_1)} \) forms a compatible system of surjective continuous \( O_k \)-linear homomorphisms, and hence induces a continuous \( O_k \)-linear homomorphism \( f: O_k^{I_0\times I_1} \twoheadrightarrow O_k^{I_0} \otimes_{O_k} O_k^{I_1} \), whose image is dense by the surjectivity of the composite with any canonical projection. Let \( c = (c_{i_0,i_1})_{(i_0,i_1)\in I_0\times I_1} \in \ker(f) \). For any \( (i_0,i_1) \in I_0 \times I_1 \), we have \( c_{i_0,i_1} = 0 \) by \( (c_{i_0,i_1} + \varphi)(\delta_{i_0,i_0} + L_0) \otimes (\delta_{i_1,i_1} + L_1) = f_{L_0,L_1}(c) = 0 \in M_{L_0,L_1} \cong (O_k/\varphi)^{I_0} \otimes_{O_k} (O_k/\varphi)^{I_1} \cong O_k/\varphi \) for any open ideal \( \varphi \subset O_k \), where \( L_0 \) and \( L_1 \) denote \( O_k^{I_0\setminus \{i_0\}} \times \varphi O_k^{\{i_0\}} \subset \mathcal{O}(O_k^{I_0}) \) and \( O_k^{I_1\setminus \{i_1\}} \times \varphi O_k^{\{i_1\}} \subset \mathcal{O}(O_k^{I_1}) \) respectively. It implies \( c = 0 \). Therefore \( f \) is injective. Since \( O_k^{I_0\times I_1} \) is compact and \( O_k^{I_0} \otimes_{O_k} O_k^{I_1} \) is Hausdorff, \( f \) is a homeomorphism.

By the definition, the completed tensor product of compact Hausdorff linear topological \( O_k \)-modules is again a compact Hausdorff linear topological \( O_k \)-module. Moreover, we show that it also preserves the flatness.

**Proposition 2.3.** For any compact Hausdorff flat linear topological \( O_k \)-modules \( M_0 \) and \( M_1 \), \( M_0 \otimes_{O_k} M_1 \) is also a compact Hausdorff flat linear topological \( O_k \)-module.

**Proof.** It is reduced to the case where \( M_0 \) and \( M_1 \) are direct products of copies of \( O_k \) by [8] Expose VII _B_ 0.3.8. Corollaire. When \( M_0 \) and \( M_1 \) are direct products of copies of \( O_k \), then the assertion immediately follows from Proposition 2.2. \( \square \)
We denote by \( \mathcal{C}^{\text{ch}}_{\text{fl}} \) the \( O_k \)-linear category of \( \mathcal{U} \)-small compact Hausdorff flat linear topological \( O_k \)-modules and continuous \( O_k \)-linear homomorphisms. By Proposition 2.3, the correspondence \( (M_0, M_1) \mapsto M_0 \hat{\otimes}_{O_k} M_1 \) restricted to \( \mathcal{U} \) gives an \( O_k \)-linear bifunctor \( \hat{\otimes}_{O_k} : \mathcal{C}^{\text{ch}}_{\text{fl}} \times \mathcal{C}^{\text{ch}}_{\text{fl}} \to \mathcal{C}^{\text{ch}}_{\text{fl}} \) and a \( k \)-linear bifunctor \( \hat{\otimes}_{O_k} : k\mathcal{C}^{\text{ch}}_{\text{fl}} \times k\mathcal{C}^{\text{ch}}_{\text{fl}} \to k\mathcal{C}^{\text{ch}}_{\text{fl}} \), for which \( \mathcal{C}^{\text{ch}}_{\text{fl}} \) and \( k\mathcal{C}^{\text{ch}}_{\text{fl}} \) naturally form symmetric monoidal categories.

A topological \( O_k \)-algebra is said to be compact Hausdorff flat linear if its underlying topological \( O_k \)-module is a compact Hausdorff flat linear topological \( O_k \)-module. It is elementary to show that the notion of a \( \mathcal{U} \)-small compact Hausdorff flat linear topological \( O_k \)-algebra is equivalent to that of a monoid object in \((\mathcal{C}^{\text{ch}}_{\text{fl}}, \hat{\otimes}_{O_k}, O_k)\).

Let \( I \) be a set. We equip \( O_k^I \) with the pointwise multiplication \( O_k^I \times O_k^I \to O_k^I \), for which it forms a commutative compact Hausdorff flat linear topological \( O_k \)-algebra and hence a commutative monoid object in \((\mathcal{C}^{\text{ch}}_{\text{fl}}, \hat{\otimes}_{O_k}, O_k)\) as long as \( I \) is \( \mathcal{U} \)-small.

Let \( G \) be a profinite group. We denote by \( O_k[[G]] \) the compact Hausdorff flat linear topological \( O_k \)-algebra given as the inverse limit of \( ((O_k/\varnothing)[G/K])_{(\varnothing, K)} \) with respect to the canonical projections, where \( \varnothing \) runs through all open ideals of \( O_k \) and \( K \) runs through all open normal subgroups of \( G \), and hence forms a monoid object in \((\mathcal{C}^{\text{ch}}_{\text{fl}}, \hat{\otimes}_{O_k}, O_k)\) as long as \( G \) is \( \mathcal{U} \)-small. The canonical embedding \( \iota_G : O_k[G] \to O_k[[G]] \) is an \( O_k \)-algebra homomorphism whose image generates a dense \( O_k \)-subalgebra, and hence \( O_k[[G]] \) is an analogue of \( O_k[G] \).

We denote by \( \text{Alg}(O_k) \) the category of monoid objects in \((\mathcal{C}^{\text{ch}}_{\text{fl}}, \hat{\otimes}_{O_k}, O_k)\) and monoid homomorphisms, and by \( \text{CAlg}(O_k) \subset \text{Alg}(O_k) \) the full subcategory of commutative monoid objects in \((\mathcal{C}^{\text{ch}}_{\text{fl}}(k), \hat{\otimes}_{O_k}, O_k)\). The correspondence \( G \mapsto O_k[[G]] \) restricted to \( \mathcal{U} \) gives a functor \( O_k[[\bullet]] : \text{PGrp} \to \text{Alg}(O_k) \), which induces a functor \( \text{PAb} \to \text{CAlg}(O_k) \).

### 2.2 Banach space

A Banach \( k \)-vector space is a \( k \)-vector space \( V \) equipped with a map \( \| \cdot \| : V \to [0, \infty) \) called the norm satisfying the following:

(i) The map \( V \times V \to [0, \infty), (v_0, v_1) \mapsto \|v_0 - v_1\| \) is a complete ultrametric.
(ii) For any \((c, v) \in k \times V\), \(\|cv\| = |c| \|v\|\) holds.

We say that \(V\) is **unramified** if \(\|v\| \in \{|c| \mid c \in k\}\) for any \(v \in V\). We put \(V^\circ := \{v \in V \mid \|v\| \leq 1\}\).

**Example 2.4.** Let \(X\) be a topological space, and \(V\) a Banach \(k\)-vector space, e.g. \(k\). We denote by \(C_{bd}(X, V) \subset C(X, V)\) the \(k\)-vector subspace of bounded continuous maps. Then \(C_{bd}(X, V)\) forms a Banach \(k\)-vector space with respect to the supremum norm \(\| \bullet \| : C_{bd}(X, V) \to [0, \infty), f \mapsto \sup_{x \in X} \|f(x)\|\). If \(V\) is unramified, then so is \(C_{bd}(X, V)\), because \(\{|c| \mid c \in k\}\) is closed in \([0, \infty)\) by the discreteness of the valuation. We denote by \(C_{0}(X, V) \subset C_{bd}(X, V)\) the \(k\)-vector subspace of functions \(f : X \to V\) such that for any \(\epsilon \in (0, \infty)\), there is a compact subset \(C \subset X\) such that \(\|f(x)\| < \epsilon\) for any \(x \in X \setminus C\). Then \(C_{0}(X, V)\) is closed in \(C_{bd}(X, V)\), and hence forms a Banach \(k\)-vector space with respect to the restriction of the supremum norm. Suppose that \(X\) is compact. Then we have \(C_{0}(X, V) = C_{bd}(X, V) = C(X, V)\) by the maximal modulus principle, and hence regard \(C(X, V)\) as a Banach \(k\)-vector space.

**Example 2.5.** Let \(M\) be a compact Hausdorff flat linear topological \(O_{k}\)-module. We denote by \(M^{Dh}_{fl} \subset C(M, k)\) the \(k\)-vector subspace of continuous \(O_{k}\)-linear homomorphisms \(M \to k\). Then \(M^{Dh}_{fl}\) is closed in \(C_{bd}(M, k)\), and hence forms a Banach \(k\)-vector space with respect to the restriction of the supremum norm.

Let \(V_0\) and \(V_1\) be Banach \(k\)-vector spaces, and \(f : V_0 \to V_1\) a \(k\)-linear homomorphism. We say that \(f\) is **bounded** if there is a \(C \in (0, \infty)\) such that \(\|f(v)\| \leq C\|v\|\) for any \(v \in V_0\), and is **submetric** (respectively, **isometric**) if \(\|f(v)\| \leq \|v\|\) (respectively, \(\|f(v)\| = \|v\|\)) for any \(v \in V_0\). Since the valuation of \(k\) is not trivial, a \(k\)-linear homomorphism between Banach \(k\)-vector spaces is bounded if and only if it is continuous by [2] 2.1.8 Corollary 3.

Let \(V_0\) and \(V_1\) be Banach \(k\)-vector spaces. We denote by \(V_1 \hat{\otimes}_k V_2\) the completed non-Archimedean tensor product of \(V_1\) and \(V_2\) (cf. [1] p. 12). We give an explicit example of the completed tensor product analogous to the one in Proposition 2.2.

**Proposition 2.6.** Let \(I_0\) and \(I_1\) be discrete sets. Then there is a natural **isometric** \(k\)-linear isomorphism \(C_{0}(I_0, k) \hat{\otimes}_k C_{0}(I_1, k) \to C_{0}(I_0 \times I_1, k)\).
Proof. Take a uniformiser \( \varpi \in O_k \). Put \( V_0 := C_0(I_0,k)^{\widehat{\otimes}}kC_0(I_1,k) \) and \( V_1 := C_0(I_0 \times I_1,k) \). Since \( V_0 \) and \( V_1 \) are naturally identified with the \( \varpi \)-adic completion of \( O_k^{\widehat{\otimes}}I_0 \otimes_{O_k} O_k^{\widehat{\otimes}}I_1 \) and \( O_k^{\widehat{\otimes}}(I_0 \times I_1) \) respectively, the \( O_k \)-linear isomorphism \( O_k^{\widehat{\otimes}}I_0 \otimes_{O_k} O_k^{\widehat{\otimes}}I_1 \to O_k^{\widehat{\otimes}}(I_0 \times I_1) \) associated to \( \text{id}_{I_0 \times I_1} \) extends to a unique continuous \( O_k \)-linear isomorphism \( V_0 \to V_1 \), which extends to a unique isometric \( k \)-linear isomorphism \( V_0 \to V_1 \).

We denote by \( \text{Ban}(k) \) (respectively, \( \text{Ban}_{\leq}(k) \)) the \( k \)-linear (respectively, \( O_k \)-linear) category of \( \mathcal{U} \)-small Banach \( k \)-vector spaces and bounded (respectively, submetric) \( k \)-linear homomorphisms, by \( \text{Ban}_{ur}^{\leq}(k) \subset \text{Ban}_{\leq}(k) \) the full subcategory of \( \mathcal{U} \)-small unramified Banach \( k \)-vector spaces. The correspondence \( I \rightsquigarrow C_0(I,k) \) restricted to \( \mathcal{U} \) gives a functor \( C_0(\bullet,k) : \text{Set} \to \text{Ban}_{\leq}(k) \). The correspondence \( (V_0,V_1) \rightsquigarrow V_0 \otimes_k V_1 \) restricted to \( \mathcal{U} \) gives a \( k \)-linear (respectively, an \( O_k \)-linear) bifunctor \( \widehat{\otimes}_k : \text{Ban}(k) \times \text{Ban}(k) \to \text{Ban}(k) \) (respectively, \( \text{Ban}_{ur}^{\leq}(k) \times \text{Ban}_{ur}^{\leq}(k) \to \text{Ban}_{ur}^{\leq}(k) \)), for which \( \text{Ban}(k) \) (respectively, \( \text{Ban}_{ur}^{\leq}(k) \)) naturally forms a symmetric monoidal category.

**Proposition 2.7.** The localisation \( k\text{Ban}_{ur}^{\leq}(k) \to \text{Ban}(k) \) of the inclusion \( \text{Ban}_{ur}^{\leq}(k) \hookrightarrow \text{Ban}(k) \) is an equivalence of category.

Proof. The following proof is essentially the same as the argument in the proof of [9] Theorem 1.2, in which \( k \) is assumed to be of characteristic 0. Denote by \( F \) the functor in the assertion. The fullness of \( F \) follows from the definition of a bounded homomorphism and non-triviality of the valuation of \( k \). The faithfulness of \( F \) follows from the flatness of hom modules. For a Banach \( k \)-vector space \( V \), denote by \( V^{ur} \) the underlying \( k \)-vector space of \( V \) equipped with the norm \( V^{ur} \to [0,\infty), v \mapsto \inf\{|c| \mid c \in k \land \|v\| \leq |c|\} \). Then \( V^{ur} \) forms a Banach \( k \)-vector space, and the identity map \( I_V : V \to V^{ur} \) is an isomorphism in \( \text{Ban}(k) \). The correspondence \( V \rightsquigarrow V^{ur} \) restricted to \( \mathcal{U} \) gives an endofunctor \( (\bullet)^{ur} \) of \( \text{Ban}(k) \), and the correspondence \( V \rightsquigarrow I_V \) restricted to \( \mathcal{U} \) gives a natural equivalence \( I : \text{id}_{\text{Ban}(k)} \Rightarrow (\bullet)^{ur} \). Moreover, \( I_V \) is the identity for any unramified Banach \( k \)-vector space \( V \). Therefore \( (\bullet)^{ur} \) induces a quasi-inverse of \( F \), because \( F \) is fully faithful.

A Banach \( k \)-algebra is a Banach \( k \)-vector space \( A \) equipped with a \( k \)-algebra structure satisfying \( \|f_0f_1\| \leq \|f_0\| \|f_1\| \) for any \( (f_0,f_1) \in A^2 \) and \( \|1\| = 1 \) as long as \( A \) is not a zero ring. It is elementary to show that the notion of a \( \mathcal{U} \)-small Banach \( k \)-algebra is equivalent to that of a monoid.
object in \((\text{Banur}_\leq, \hat{\otimes}_k, k)\). We note that there are several distinct formulations of the notion of a Banach \(k\)-algebra, and such an equivalence does not necessarily hold if one applies another formulation.

Let \(X\) be a topological space. We equip \(C_{\text{bd}}(X, k)\) with the pointwise multiplication \(C_{\text{bd}}(X, k) \times C_{\text{bd}}(X, k) \to C_{\text{bd}}(X, k)\), for which it forms a commutative Banach \(k\)-algebra and hence a commutative monoid object in \((\text{Banur}_\leq, \hat{\otimes}_k, k)\) as long as \(X\) is \(\mathcal{U}\)-small.

In order to introduce another example of a monoid object in \((\text{Banur}_\leq, \hat{\otimes}_k, k)\), we recall the notion of a (possibly uncountable) infinite sum. Let \(I\) be a discrete set, and \(f: I \to k\) a map. We denote by \(\sum_{i \in I} f(i)\) the limit of the net \((\sum_{J \subset I, \# J < \infty} f(i))_{J \subset I}\) indexed by the set of finite subsets \(J \subset I\) directed with respect to the inclusion relation. When \(I = \{i \in \mathbb{N} \mid i < n\}\) (respectively, \(I = \mathbb{N}\)), then \(\sum_{i \in I} f(i)\) coincides with the usual finite sum \(\sum_{i = 0}^{n-1} f(i)\) (respectively, the usual infinite sum \(\sum_{i = 0}^{\infty} f(i)\)). Moreover, it is elementary to show that \(\sum_{i \in I} f(i)\) converges in \(k\) if and only if \(f\) lies in \(C_0(I, k)\).

Let \(G\) be a discrete group. We equip \(C_0(G, k)\) with the convolution product

\[
C_0(G, k) \times C_0(G, k) \to C_0(G, k), \quad ((c_g)_{g \in G}, (d_g)_{g \in G}) \mapsto \left(\sum_{h \in G} c_h d_{h^{-1} g}\right)_{g \in G},
\]

where the sum in the definition makes sense by the argument above, for which it forms a Banach \(k\)-algebra and hence a monoid object in \((\text{Banur}_\leq, \hat{\otimes}_k, k)\) as long as \(G\) is \(\mathcal{U}\)-small. The canonical embedding \(\iota^G_k: k[G] \to C_0(G, k)\) is an \(k\)-algebra homomorphism whose image is dense, and hence \(C_0(G, k)\) is an analogue of \(k[G]\).

We denote by \(\text{Alg}(k)\) the category of monoid objects in \((\text{Banur}_\leq(k), \hat{\otimes}_k, k)\) and monoid homomorphisms, and by \(\text{CAlg}(k) \subset \text{Alg}(k)\) the full subcategory of commutative monoid objects in \((\text{Banur}_\leq(k), \hat{\otimes}_k, k)\). The correspondence \(G \rightsquigarrow C_0(G, k)\) restricted to \(\mathcal{U}\) gives a functor \(C_0(\bullet, k): \text{Grp} \to \text{Alg}(k)\), which induces a functor \(\text{Ab} \to \text{CAlg}(k)\). The correspondence \(X \rightsquigarrow C_{\text{bd}}(X, k)\) restricted to \(\mathcal{U}\) gives a functor \(C_{\text{bd}}(\bullet, k): \text{Top}^{\text{op}} \to \text{CAlg}(k)\). We recall non-Archimedean Gel’fand–Naimark theorem.

**Proposition 2.8.** The functor \(C_{\text{bd}}(\bullet, k)\) restricted to \(\text{PTop}\) is fully faithful.

**Proof.** The assertion immediately follows from [1] 9.2.7 Corollary. \(\square\)
3 Monoidal Structure

We introduce symmetric monoidal structures on Ban$_{\leq}(k)$, Ban$(k)$, C(ch), and $k\mathcal{C}_{\flat}$, and verify the monoidal functoriality of Schikhof duality (cf. [6] Theorem 4.6 and [9] Theorem 1.2). As a corollary, we obtain a duality between Hopf monoid objects.

3.1 Monoidal functoriality Let $V$ be a Banach $k$-vector space. We denote by $V^{\text{DBan}}$ the $O_k$-module of submetrix $k$-linear homomorphism $V \to k$ equipped with the topology of pointwise convergence. Then $V^{\text{DBan}}$ forms a compact Hausdorff flat linear topological $O_k$-module because $O_k$ equipped with the direct product topology is a compact Hausdorff flat linear topological $k$-module and the evaluation map $V^{\text{DBan}} \to O_k^\ast$, $m \mapsto (m(v))_{v \in V^\ast}$ is a homeomorphism onto the closed image. The correspondence $V \sim \to V^{\text{DBan}}$ restricted to $\mathcal{U}$ gives a functor $D_{\text{Ban}}: \text{Ban}_{\leq}(k)^{\text{op}} \to \mathcal{C}_{\flat}$. We put $D_{\text{Ban}}^{\text{ur}} := D_{\text{Ban}}|_{\text{Ban}_{\leq}(k)^{\text{op}}}$.

Example 3.1. For any profinite group $G$, $C(G, k)^{D_{\text{Ban}}^{\text{ur}}}$ is naturally identified with $O_k[[G]]$ through a unique continuous $O_k$-bilinear extension $O_k[[G]] \times C(G, k) \to k$ of the canonical pairing $O_k[G] \times C(G, k) \to k$, $(c_g)_{g \in G} \otimes f \mapsto \sum_{g \in G} c_g f(g)$ through $\nu_G \times \text{id}_{C(G,k)}$.

On the other hand, let $M$ be a compact Hausdorff flat linear topological $O_k$-module. For any continuous $O_k$-linear homomorphism $v: M \to k$, its supremum norm $\|v\| := \sup_{m \in M} |v(m)|$ is finite by the compactness of $M$. We denote by $M^{D_{\text{fl}}^{\text{ch}}}$ the $k$-vector space of continuous $O_k$-linear homomorphisms $M \to k$ equipped with the supremum norm. Then $M^{D_{\text{fl}}^{\text{ch}}}$ forms an unramified Banach $k$-vector space by the discreteness of the valuation of $k$.

For a Banach $k$-vector space $V$, we denote by $\eta_{\text{Ban}}(V): V \to V^{\text{DBan}}D_{\text{fl}}^{\text{ch}}$ the evaluation map. For a compact Hausdorff flat linear topological $O_k$-module $M$, we denote by $\eta_{\text{fl}}^{\text{ch}}(M): M \to M^{D_{\text{fl}}^{\text{ch}}}$ the evaluation map. The correspondences $V \sim \eta_{\text{Ban}}(V)$ and $M \sim \eta_{\text{fl}}^{\text{ch}}(M)$ restricted to $\mathcal{U}$ give natural transformations $\eta_{\text{Ban}}: \text{id}_{\text{Ban}_{\leq}(k)^{\text{op}}} \Rightarrow D_{\text{fl}}^{\text{ch}} \circ D_{\text{Ban}}$ and $\eta_{\text{fl}}^{\text{ch}}: \text{id}_{\mathcal{C}_{\flat}} \Rightarrow D_{\text{Ban}} \circ D_{\text{fl}}^{\text{ch}}$. By Schikhof duality, $\eta_{\text{Ban}}(V)$ and $\eta_{\text{fl}}^{\text{ch}}(M)$ (respectively, $k\eta_{\text{fl}}^{\text{ch}}(M)$) are isomorphisms in $\text{Ban}_{\leq}(k)$ and $\mathcal{C}_{\flat}$ (respectively, Ban$(k)$ and $k\mathcal{C}_{\flat}$) respectively for any $\mathcal{U}$-small unramified Banach $k$-vector space $V$ (respectively, $\mathcal{U}$-small Banach $k$-vector space $V$) and any $\mathcal{U}$-small compact Hausdorff flat linear topological $k$-module because $\mathcal{U}$-small compact Hausdorff flat linear topological $k$-modules are compact Hausdorff flat linear topological $O_k$-modules.
Duality theory of $p$-adic Hopf algebras

dorff flat linear topological $O_k$-module $M$, and $(\text{D}_{\text{Ban}}^{ur}, D_{\text{fl}}^{ch})$ (respectively, $(\text{D}_{\text{Ban}}, kD_{\text{fl}}^{ch})$) gives an equivalence of categories between $\text{Ban}_{\leq}^{ur}(k)$ and $\mathcal{C}_{fl}^{ch}$ (respectively, $\text{Ban}(k)$ identified with $k\text{Ban}_{\leq}^{ur}(k)$ by Proposition 3.13 and $k\mathcal{C}_{fl}^{ch}$). Further, we show the compatibility with the other structures.

**Theorem 3.2.** The pair $(\text{D}_{\text{Ban}}^{ur}, D_{\text{fl}}^{ch})$ (respectively, $(\text{D}_{\text{Ban}}, kD_{\text{fl}}^{ch})$) gives an equivalence of symmetric monoidal $O_k$-linear categories $(\text{Ban}^{ur}_k(k), \hat{\otimes}_k, k)^{op}$ and $(\mathcal{C}_{fl}^{ch}, \otimes_{O_k}, O_k)$ (respectively, symmetric monoidal $k$-linear categories $(\text{Ban}(k), \hat{\otimes}_k, k)^{op}$ and $(k\mathcal{C}_{fl}^{ch}, \otimes_{O_k}, O_k)$).

In order to verify Theorem 3.2, we prepare several lemmas.

**Lemma 3.3.** The correspondence $I \leadsto O_k^I$ (respectively, $C_0(I, k)$) restricted to $\mathcal{U}$ gives a symmetric monoidal functor $O_k^\bullet: (\text{Set}, \times, 1) \to (\mathcal{C}_{fl}^{ch}, \hat{\otimes}_{O_k}, O_k)^{op}$ (respectively, $C_0(\bullet, k): (\text{Set}, \times, 1) \to (\text{Ban}^{ur}_k(k), \hat{\otimes}_k, k)$).

**Proof.** The functoriality is obvious. We show that the functors are compatible with the symmetric monoidal structures. For $\mathcal{U}$-small sets $I_0$ and $I_1$, denote by $T(I_0, I_1)$ the isomorphism $O_k^{I_0 \times I_1} \to O_k^{I_0} \hat{\otimes}_k O_k^{I_1}$ in $\mathcal{C}_{fl}^{ch}$ (respectively, $C_0(I_0, k)\hat{\otimes}_k C_0(I_1, k) \to C_0(I_0 \times I_1, k)$ in $\text{Ban}_{\leq}^{ur}(k)$) explicitly constructed in the proof of Proposition 2.2 (Proposition 2.6). The correspondence $(I_0, I_1) \leadsto T(I_0, I_1)$ gives a natural equivalence $T: O_k^{\bullet \times \bullet} \to O_k^{\bullet} \hat{\otimes}_k O_k^{\bullet}$ (respectively, $C_0(\bullet, k)\hat{\otimes}_k C_0(\bullet, k) \Rightarrow C_0(\bullet \times \bullet, k)$) with the desired coherence by the construction.

We recall classical results on classifications of unramified Banach $k$-vector spaces and compact Hausdorff flat linear topological $O_k$-modules.

**Lemma 3.4.** (i) For any unramified Banach $k$-vector space $V$, there is an isometric $k$-linear isomorphism $C_0(I, k) \to V$ for some set $I$.

(ii) For any compact Hausdorff flat linear topological $O_k$-module $M$, there is a homeomorphic $O_k$-linear isomorphism $M \to O_k^I$ for some set $I$.

**Proof.** The first assertion follows from [5] IV 3 Corollaire 1 (cf. [2] 2.5.2 Lemma 2 and the proof of [7] Proposition 10.1), and the second assertion follows from [8] Expose VII B 0.3.8. Corollaire.

**Proof of Theorem 3.2.** The linearity immediately follows from the definition of the enrichment. The localisation by $(\mathcal{C}_k, \otimes_k, k)$ is compatible with
the monoidal structures, and hence it suffices to verify that \( D_{\text{ur}}^{\text{Ban}} \) and \( D_{\text{fl}}^{\text{ch}} \) form symmetric monoidal functors by the argument on \( \eta_{\text{Ban}} \) and \( \eta_{\text{fl}}^{\text{ch}} \) in the beginning of this subsection.

We construct a natural equivalence \((\bullet_0)^{D_{\text{ur}}^{\text{Ban}}} \hat{\otimes} O_k (\bullet_1)^{D_{\text{ur}}^{\text{Ban}}} \Rightarrow (\bullet_0 \hat{\otimes} k \bullet_1)^{D_{\text{ur}}^{\text{Ban}}}
\) with the desired coherence. For this purpose, it suffices to show that the \( \mathcal{O}_k \)-linear homomorphism \( V_0^{D_{\text{ur}}^{\text{Ban}}} \otimes O_k V_1^{D_{\text{ur}}^{\text{Ban}}} \rightarrow (V_0 \hat{\otimes} k V_1)^{D_{\text{ur}}^{\text{Ban}}} \) associated to the \( \mathcal{O}_k \)-linear pairing \((V_0^{D_{\text{ur}}^{\text{Ban}}} \otimes O_k V_1^{D_{\text{ur}}^{\text{Ban}}}) \otimes O_k (V_0 \otimes O_k V_1) \cong (V_0^{D_{\text{ur}}^{\text{Ban}}} \otimes O_k V_0) \otimes O_k (V_1^{D_{\text{ur}}^{\text{Ban}}} \otimes O_k V_1) \rightarrow k \otimes O_k k \cong k \) extends to a unique homeomorphic \( \mathcal{O}_k \)-linear isomorphism \( V_0^{D_{\text{ur}}^{\text{Ban}}} \otimes O_k V_1^{D_{\text{ur}}^{\text{Ban}}} \rightarrow (V_0 \hat{\otimes} k V_1)^{D_{\text{ur}}^{\text{Ban}}} \) in \( \mathcal{O}_k \) for any unramified Banach \( k \)-vector spaces \( V_0 \) and \( V_1 \). By Lemma 3.4 (i), it is reduced to the case \( V_0 = C_0(I, k) \) and \( V_1 = C_0(J, k) \) for sets \( I \) and \( J \). By Lemma 3.3, we have a natural homeomorphic \( \mathcal{O}_k \)-linear isomorphism \( C_0(I, k)^{D_{\text{ur}}^{\text{Ban}}} \hat{\otimes} O_k C_0(J, k)^{D_{\text{ur}}^{\text{Ban}}} \cong O_k^I \hat{\otimes} O_k O_k^J \cong O_k^{I \times J} \cong C_0(I \times J, k)^{D_{\text{ur}}^{\text{Ban}}} \cong (C_0(I, k) \hat{\otimes} k C_0(J, k))^{D_{\text{ur}}^{\text{Ban}}} \) extending the given homomorphism. Therefore \( D_{\text{ur}}^{\text{Ban}} \) forms a symmetric monoidal equivalence.

We construct a natural equivalence \((\bullet_0)^{D_{\text{fl}}^{\text{ch}}} \hat{\otimes} k (\bullet_1)^{D_{\text{fl}}^{\text{ch}}} \Rightarrow (\bullet_0 \hat{\otimes} O_k \bullet_1)^{D_{\text{fl}}^{\text{ch}}}
\) with the desired coherence. For this purpose, it suffices to show that the \( \mathcal{O}_k \)-linear homomorphism \( M_0^{D_{\text{fl}}^{\text{ch}}} \otimes k M_1^{D_{\text{fl}}^{\text{ch}}} \rightarrow (M_0 \hat{\otimes} O_k M_1)^{D_{\text{fl}}^{\text{ch}}} \) associated to the \( \mathcal{O}_k \)-linear pairing \((M_0^{D_{\text{fl}}^{\text{ch}}} \otimes k M_1^{D_{\text{fl}}^{\text{ch}}}) \otimes O_k (M_0 \otimes O_k M_1) \cong (M_0^{D_{\text{fl}}^{\text{ch}}} \otimes O_k M_0) \otimes O_k (M_1^{D_{\text{fl}}^{\text{ch}}} \otimes O_k M_1) \rightarrow k \otimes O_k k \cong k \) extends to a unique isometric \( \mathcal{O}_k \)-linear isomorphism \( M_0^{D_{\text{fl}}^{\text{ch}}} \otimes k M_1^{D_{\text{fl}}^{\text{ch}}} \rightarrow (M_0 \hat{\otimes} O_k M_1)^{D_{\text{fl}}^{\text{ch}}} \) for any compact Hausdorff flat linear topological \( \mathcal{O}_k \)-modules \( M_0 \) and \( M_1 \). By Lemma 3.4 (ii), it is reduced to the case \( M_0 = O_k^{I_0} \) and \( M_1 = O_k^{I_1} \) for sets \( I_0 \) and \( I_1 \). By Lemma 3.3, we have a natural isometric \( \mathcal{O}_k \)-linear isomorphism \((O_k^{I_0})^{D_{\text{fl}}^{\text{ch}}} \hat{\otimes} (O_k^{I_1})^{D_{\text{fl}}^{\text{ch}}} \cong C_0(I_0, k) \hat{\otimes} k C_0(I_1, k) \cong C_0(I_0 \times I_1, k) \) extending the given homomorphism. Therefore \( D_{\mathcal{O}_k} \) and \( D_{\mathcal{O}_k}^{\text{ch}} \) are symmetric monoidal functors.

We also have a relation to Cartesian products of topological spaces.

**Corollary 3.5.** (i) For any profinite groups \( G_0 \) and \( G_1 \), the \( \mathcal{O}_k \)-algebra isomorphism \( \mathcal{O}_k[G_0] \otimes \mathcal{O}_k [G_1] \rightarrow \mathcal{O}_k[G_0 \times G_1] \) associated to \( \text{id}_{G_0 \times G_1} \) extends to a unique homeomorphic \( \mathcal{O}_k \)-algebra isomorphism \( \mathcal{O}_k[[G_0]] \hat{\otimes} \mathcal{O}_k [G_1] \rightarrow \mathcal{O}_k[[G_0 \times G_1]] \).
(ii) For any topological spaces $X_0$ and $X_1$, the $k$-algebra homomorphism $C_{bd}(X_1, k) \otimes_k C_{bd}(X_0, k) \to C_{bd}(X_0 \times X_1, k)$, $(f_1(x_1), f_0(x_0)) \mapsto f_0(x_0)f_1(x_1)$ extends to a unique isometric $k$-algebra isomorphism

$$C_{bd}(X_1, k) \hat{\otimes}_k C_{bd}(X_0, k) \to C_{bd}(X_0 \times X_1, k).$$

**Proof.** The assertion (i) immediately follows from Theorem 3.2 and the assertion (ii) applied to the underlying topological spaces of $G_0$ and $G_1$. We show the assertion (ii). In the case where $X_0$ and $X_1$ are totally disconnected compact Hausdorff topological spaces, the assertion immediately follows from Proposition 2.8, because $\hat{\otimes}_k$ satisfies the universality of the coproduct. In the general case, the assertion follows from the fact that the inclusion $PTop \hookrightarrow \text{Top}$ is a right adjoint functor (cf. [4] Corollary 2.3). We note that the universality and the adjoint property are formalisable without using categories, and hence we do not have to assume the $\mathcal{U}$-smallness of $X_0$ and $X_1$. \qed

### 3.2 Hopf monoid

For a symmetric monoidal category $(\mathcal{S}, \otimes, I)$, we denote by $\text{Hopf}(\mathcal{S}, \otimes, I)$ the category of Hopf monoid objects in $(\mathcal{S}, \otimes, I)$ and Hopf monoid homomorphisms. As an immediate consequence of Theorem 3.2, we obtain the following:

**Theorem 3.6.** The pair $(\mathcal{D}_{\text{Ban}}^\text{ur}, \mathcal{D}_{\text{ch}}^\text{fl})$ (respectively, $(\mathcal{D}_{\text{Ban}}, k\mathcal{D}_{\text{ch}}^\text{fl})$) gives an equivalence of categories $\text{Hopf}(\text{Ban}_{\leq}^\text{ur}(k), \hat{\otimes}_k, k)^{\text{op}}$ and $\text{Hopf}(\mathcal{C}_{\text{ch}}^\text{fl}, \hat{\otimes}_{O_k}, O_k)$ (respectively, $\text{Hopf}(\text{Ban}(k), \hat{\otimes}_k, k)^{\text{op}}$ and $\text{Hopf}(k\mathcal{C}_{\text{ch}}^\text{fl}, \hat{\otimes}_{O_k}, O_k)$).

We give an explicit example of a Hopf monoid object in $(\mathcal{C}_{\text{ch}}^\text{fl}, \hat{\otimes}_{O_k}, O_k)$. We recall one of the simplest example of a Hopf $O_k$-algebra, that is, a Hopf monoid object in $(\mathcal{S}, \otimes_{O_k}, O_k)$, is the group algebra over $O_k$. Similarly, we construct two sorts of Hopf monoid objects in $(\mathcal{C}_{\text{ch}}^\text{fl}, \hat{\otimes}_{O_k}, O_k)$ by using a topological group.

**Proposition 3.7.** (i) Let $G$ be a $\mathcal{U}$-small profinite group. Then the monoid object structure of $O_k[[G]]$ in $(\mathcal{C}_{\text{ch}}^\text{fl}, \hat{\otimes}_{O_k}, O_k)$ extends to a unique Hopf monoid object structure in $(\mathcal{C}_{\text{ch}}^\text{fl}, \hat{\otimes}_{O_k}, O_k)$ such that $\iota^G$ preserves the comultiplication, the counit, and the antipode. Moreover, $O_k[[G]]$ is cocommutative.

(ii) Let $G$ be a $\mathcal{U}$-small discrete group. Then the monoid object structure of $C_0(G, k)$ in $(\text{Ban}_{\leq}^\text{ur}, \hat{\otimes}_k, k)$ extends to a unique Hopf monoid object
structure in \((\text{Ban}_\leq^\text{ur}(k), \hat{\otimes}_k, k)\) such that \(\iota^d_G\) preserves the comultiplication, the counit, and the antipode. Moreover, \(C_0(G, k)\) is cocommutative.

**Proof.** (i) The uniqueness and the cocommutativity follow from the fact that the image of \(\iota^c_G\) is dense in \(O_k[[G]]\). The system \(((O_k/\varphi)[G/K])_{(\varphi, K)}\) forms an inverse system in the under category \(O_k[G]/\text{Hopf}(\mathcal{C}, \otimes_{O_k}, O_k)\) with respect to the canonical projections, where \(\varphi\) runs through open ideals of \(O_k\) and \(K\) runs through open normal subgroups of \(G\). By the definition of \(\hat{\otimes}_{O_k}\), the systems of comultiplications, counits, and antipodes induce a comultiplication, a counit, and an antipode on \(O_k[[G]]\) respectively with respect to \((\hat{\otimes}_{O_k}, O_k)\), for which \(O_k[[G]]\) forms a Hopf monoid object in \((\mathcal{C}_\text{ur}^\text{ch}, \hat{\otimes}_{O_k}, O_k)\) satisfying the desired conditions again because the image of \(\iota^c_G\) is dense in \(O_k[[G]]\).

(ii) The uniqueness and the cocommutativity follow from the fact that the image of \(\iota^d_G\) is dense in \(C_0(G, k)\). Take a uniformiser \(\varpi \in O_k\). Since \(C_0(G, k)^\circ\) is naturally identified with the \(\varpi\)-adic completion of \(O_k[G]\), the Hopf \(O_k\)-algebra structure of \(O_k[G]\) induces a comultiplication \(C_0(G, k)^\circ \to (C_0(G, k) \hat{\otimes}_k C_0(G, k))^\circ\), a counit \(C_0(G, k)^\circ \to O_k\), and an antipode \(C_0(G, k)^\circ \to C_0(G, k)^\circ\), which extend to a comultiplication, a counit, and an antipode on \(C_0(G, k)\) respectively with respect to \((\hat{\otimes}_k, k)\), for which \(C_0(G, k)\) forms a Hopf monoid object in \((\text{Ban}_\leq^\text{ur}(k), \hat{\otimes}_k, k)\) satisfying the desired conditions again because the image of \(\iota^d_G\) is dense in \(C_0(G, k)\). \(\square\)

**Corollary 3.8.** (i) Let \(G\) be a \(\mathcal{U}\)-small profinite group. Then the monoid object structure of \(C(G, k)\) extends to a unique Hopf monoid object structure in \((\text{Ban}_\leq^\text{ur}(k), \hat{\otimes}_k, k)\) such that the composite of the comultiplication and the isometric \(k\)-linear isomorphism \(\iota: C(G, k) \hat{\otimes}_k C(G, k) \to C(G \times G, k)\) in Corollary 3.5 (ii) coincides with the composition to the multiplication \(G \times G \to G\), the counit is \(\iota^c_G(1) \in O_k[[G]]\) \(\cong C(G, k)^\text{Ban}_\leq^\text{ur}\), and the antipode is the involution \(C(G, k) \to C(G, k)\) given as the composition to the map \(G \to G, g \mapsto g^{-1}\).

(ii) Let \(G\) be a \(\mathcal{U}\)-small discrete group. Then the monoid object structure of \(O_k^G\) extends to a unique Hopf monoid object structure in \((\mathcal{C}_\text{ur}^\text{ch}, \hat{\otimes}_{O_k}, O_k)\) such that the composite of the comultiplication and the homeomorphic \(O_k\)-linear isomorphism \(O_k^G \hat{\otimes}_{O_k} O_k^G \to O_k^{G \times G}\) in Lemma 3.3 coincides with the composition to the multiplication \(G \times G \to G\), the counit is \(\iota^d_G(1) \in C_0(G, k) \cong (O_k^G)^\text{Ban}_\leq\), and the antipode is the involution \(O_k^G \to O_k^G, (c_g)_{g \in G} \mapsto (c_g^{-1})_{g \in G}\).
Proof. The assertions immediately follow from Example 3.1, Lemma 3.3, Theorem 3.6, and Proposition 3.7 by the fact that the dual of the comultiplication of $O_k[[G]]$ (respectively, $C_0(G, k)$) coincides with the pointwise multiplication of $C(G, k)$ (respectively, $O_k^G$).

4 Pontryagin duality

We introduce two sorts of $p$-adic Pontryagin dualities in terms of functors of points. Through the duality in Theorem 3.6, we establish $p$-adic analogues of Fourier transform and Plancherel’s theorem extending Amice transform $C(\mathbb{Z}_p, k) \xrightarrow{\text{DurBan}} O_k[[T]]$.

4.1 Discrete Abelian group For a Banach $k$-algebra $A$, we denote by $A^G_{m/k}$ the discrete group which shares the underlying group with $(A^c)^\times$. The correspondence $A \mapsto A^G_{m/k}$ restricted to $\mathcal{U}$ gives a functor $\mathcal{G}_{m/k}: \text{CAlg}(k) \to \text{Ab}$, which is a multiplicative analytic group over $k$ because it is the kernel of the natural transformation $\mathcal{G}_{m/k} \to \mathcal{G}_{m/k}$ given by the $n$-th power.

Example 4.1. (i) Let $n \in \mathbb{N} \setminus \{0\}$. For a Banach $k$-algebra $A$, we denote by $A^{\mu^n_{n/k}} \subset A^G_{m/k}$ the subgroup $\{f \in A^G_{m/k} \mid f^n = 1\}$. The correspondence $A \mapsto A^{\mu^n_{n/k}}$ restricted to $\mathcal{U}$ gives a functor $\mu^n_{n/k}: \text{CAlg}(k) \to \text{Ab}$, which is a multiplicative analytic group over $k$ because it is the kernel of the natural transformation $G_{m/k} \to G_{m/k}$ given by the $n$-th power.

(ii) Let $D_{\mathbb{N}}$ denote the set $\{(n_0, n_1) \in (\mathbb{N} \setminus \{0\})^2 \mid \exists d \in \mathbb{N}, dn_0 = n_1\}$. For a Banach $k$-algebra $A$, we denote by $A^{\hat{\mathbb{Z}}(1)/k}$ the inverse limit of $(A^{\mu^n_{n/k}})_{n \in \mathbb{N}\setminus\{0\}}$ with respect to the system of $n_0^{-1}n_1$-th powers $A^{\mu_{n_1/k}} \to A^{\mu_{n_0/k}}$ indexed by $(n_0, n_1) \in D_{\mathbb{N}}$ equipped with the discrete topology. The correspondence $A \mapsto A^{\hat{\mathbb{Z}}(1)/k}$ restricted to $\mathcal{U}$ gives a functor $\hat{\mathbb{Z}}(1)/k: \text{CAlg}(k) \to \text{Ab}$,
which is a multiplicative analytic group over \( k \) because it is the kernel of the natural transformation
\[
\mathbb{G}^N_m \to \mathbb{G}_m^D, \quad (f_n)_{n \in \mathbb{N}} \mapsto (f_n^{-1} f_n^{-1})_{(n_0, n_1) \in D_N}.
\]

For discrete Abelian groups \( G \) and \( H \), we denote by \( \mathcal{H} \text{om}_{\text{Ab}}(G, H) \) the discrete set of group homomorphisms \( G \to H \) equipped with the pointwise multiplication. Let \( G \) be a \( \mathcal{U} \)-small discrete Abelian group. The correspondence \( A \sim \mathcal{H} \text{om}_{\text{Ab}}(G, A^\mathbb{G}_m/k) \) restricted to \( \mathcal{U} \) gives a functor \( \mathcal{H} \text{om}_{\text{Ab}}(G, \mathbb{G}_m/k): \text{CAlg}(k) \to \text{Ab} \). Since \( \mathbb{G}_m/k \) is a counterpart of \( S^1 \), \( \text{Hom}_{\text{Ab}}(\bullet, \mathbb{G}_m/k) \) is a \( p \)-adic analogue of the Pontryagin dual.

**Proposition 4.2.** For any \( \mathcal{U} \)-small discrete Abelian group \( G \),

\[
\mathcal{H} \text{om}_{\text{Ab}}(G, \mathbb{G}_m/k)
\]

forms a multiplicative analytic group over \( k \).

In order to verify Proposition 4.2, we prepare several lemmata.

**Lemma 4.3.** For any \( \mathcal{U} \)-small discrete Abelian group \( G \), \( \mathcal{H} \text{om}_{\text{Ab}}(G, \mathbb{G}_m/k) \) is representable by \( C_0(G, k) \).

**Proof.** By Proposition 3.7 (ii), \( C_0(G, k) \) represents a functor \( \hat{G}: \text{CAlg}(k) \to \text{Ab} \). Denote by \( u \in \mathcal{H} \text{om}_{\text{Ab}}(G, C_0(G, k)^\mathbb{G}_m/k) \) the composite of the canonical embedding \( G \hookrightarrow k[G] \) and \( \iota_G^{(k)} \), and by \( F \) the natural transformation \( \hat{G} \Rightarrow \mathcal{H} \text{om}_{\text{Ab}}(G, \mathbb{G}_m/k) \) determined by the equality \( F(C_0(G, k))(\iota_{C_0(G, k)}) = u \) by Yoneda’s lemma because \( u \) is a group homomorphism. We show that \( F \) is a natural equivalence. Let \( A \) be a commutative monoid object in \( (\text{Ban}_{\leq}(k), \hat{\otimes}, k) \). Then \( F(A) \) is the group homomorphism

\[
\text{Hom}_{\text{CAlg}(k)}(C_0(G, k), A) \to \mathcal{H} \text{om}_{\text{Ab}}(G, A^\mathbb{G}_m/k), \quad \varphi \mapsto \varphi \circ u.
\]

Since the image of \( u \) generates a dense \( k \)-subalgebra of \( C_0(G, k) \), \( F(A) \) is injective. Let \( \psi \in \mathcal{H} \text{om}_{\text{Ab}}(G, A^\mathbb{G}_m/k) \). For any \( g \in G \), we have \( \|\psi(g)\| = 1 \) by \( \psi(g) \in (A^\circ)^\times \). Therefore the \( k \)-algebra homomorphism \( \varphi: k[G] \to A \) associated to \( \psi \) by the universality of the group algebra satisfies \( \|\varphi(f)\| \leq \|\iota_G^d(f)\| \) for any \( f \in k[G] \). It implies that \( \varphi \) extends to a unique subalgebra homomorphism \( \widehat{\varphi}: C_0(G, k) \to A \) through \( \iota_G^d \), because the image of \( \iota_G^d \) is dense in \( C_0(G, k) \). We have \( F(A)(\widehat{\varphi}) = \widehat{\varphi} \circ u = \psi \). It implies the surjectivity of \( F(A) \). Thus \( F \) is a natural equivalence. \( \square \)
Corollary 4.4. For any $\mathcal{U}$-small set $I$, $G_m^I$ is representable by $C_0(\mathbb{Z}_{m/k}^I, k)$.

Proof. The assertion immediately follows from Lemma 4.3 applied to the case $G = \mathbb{Z}_{m/k}^I$ by the universality of the direct sum, because the identity functor $\text{Ab} \rightarrow \text{Ab}$ is represented by $\mathbb{Z}$.

Proof of Proposition 4.2. Denote by $\varphi_0$ the group homomorphism $\mathbb{Z}^{\oplus G} \rightarrow G$ associated to $\text{id}_G$, and by $\varphi_1$ the group homomorphism $\mathbb{Z}^{\oplus \ker(\varphi_0)} \rightarrow \mathbb{Z}^{\oplus G}$ associated to the inclusion $\ker(\varphi_0) \hookrightarrow \mathbb{Z}^{\oplus G}$. By Proposition 3.7 (ii),

$$C_0(\varphi_0, k) : C_0(\mathbb{Z}^{\oplus G}, k) \rightarrow C_0(G, k)$$

and $C_0(\varphi_1, k) : C_0(\mathbb{Z}^{\oplus \ker(\varphi_0)}, k) \rightarrow C_0(\mathbb{Z}^{\oplus G}, k)$ form Hopf monoid homomorphisms. By Lemma 4.3 and Corollary 4.4, they induce natural transformations $F_0 : \mathcal{H}om_{\text{Ab}}(G, G_m/k) \Rightarrow G_m^G$ and $F_1 : G_m^G \Rightarrow G_m^G$. We show that $(\mathcal{H}om_{\text{Ab}}(G, G_m/k), F_0)$ satisfies the universality of the kernel of $F_1$.

By $\varphi_1 \circ \varphi_0 = 0$, we have $C_0(\varphi_1, k) \circ C_0(\varphi_0, k) = C_0(0, k) = 0$, and hence $F_1 \circ F_0 = 0$. Let $A$ be a $\mathcal{U}$-small commutative monoid object in $(\text{Ban}_{\mathcal{U}}^G(k), \otimes_k, k)$. We show that $(\text{Hom}_{\text{Ab}}(G, A^G_m/k), F_0(A))$ satisfies the universality of the kernel of $F_1(A)$. By $F_1 \circ F_0 = 0$, we have $F_1(A) \circ F_0(A) = 0$. By the definition of $F_0$, $F_0(A)$ is the inclusion $\text{Hom}_{\text{Ab}}(G, A^G_m/k) \hookrightarrow (A^G_m/k)^G$. Let $f \in \ker(F_1(A)) \subset (A^G_m/k)^G$. For any $(g_0, g_1) \in G^2$, we have $g_0g_1 - g_0 - g_1 \in \ker(\varphi_0)$, and hence

$$f(g_0g_1) = (f(g_0g_1)f(g_0)^{-1}f(g_1)^{-1})f(g_0)f(g_1) = F_1(f)(g_0g_1 - g_0 - g_1)f(g_0)f(g_1) = f(g_0)f(g_1)$$

by the construction of the natural isomorphism in the proof of Lemma 4.3. It implies that $f$ is a group homomorphism $G \rightarrow A^G_m/k$, and hence is an element of the image of $F_0(A)$. Therefore $(\text{Hom}_{\text{Ab}}(G, A^G_m/k), F_0(A))$ satisfies the universality of the kernel of $F_1(A)$. It implies that $(\mathcal{H}om_{\text{Ab}}(G, G_m/k), F_0)$ satisfies the universality of the kernel of $F_1$.

We denote by $\text{PAb}_k$ the category of multiplicative analytic groups over $k$ and natural transformations. By Proposition 4.2, the correspondence $G \hookrightarrow \mathcal{H}om_{\text{Ab}}(G, G_m/k)$ gives a functor $\mathcal{H}om_{\text{Ab}}(\bullet, G_m/k) : \text{Ab}^{\text{op}} \rightarrow \text{PAb}_k$.

Now we state a $p$-adic analogue of the Pontryagin duality.

Theorem 4.5. The functor $\mathcal{H}om_{\text{Ab}}(\bullet, G_m/k)$ is fully faithful and essentially surjective.
By the axiom of choice and the smallness of Ab, Theorem 4.5 implies that \( \text{Ab}^{\text{op}} \) is naturally equivalent to \( \text{PAb}_k \). However, there seems to be no natural construction of an inverse of \( \text{Hom}_{\text{Ab}}(\cdot, \mathbb{G}_m/k) \). Although the fullness and the faithfulness immediately follows from the proof of Corollary 3.8 (ii) because the maximal spectrum of \( O_k^G \) modulo the maximal ideal of \( O_k \) is canonically homeomorphic to the Stone–Čech compactification of \( G \), we give an alternative proof constructing an ”inverse correspondence”. In order to verify Theorem 4.5, we prepare several notions and lemmata.

Let \( \mathcal{G} \) be a multiplicative analytic group over \( k \). We denote by \( \text{Hom}_{\text{PAb}_k}(\mathcal{G}, \mathbb{G}_m/k) \) the discrete set \( \text{Hom}_{\text{PAb}_k}(\mathcal{G}, \mathbb{G}_m/k) \) equipped with the pointwise multiplication. We note that \( \text{Hom}_{\text{PAb}_k}(\mathcal{G}, \mathbb{G}_m/k) \) is not \( \mathcal{U} \)-small in our context, and hence is not an object of Ab. Therefore the correspondence \( \mathcal{G} \mapsto \text{Hom}_{\text{PAb}_k}(\mathcal{G}, \mathbb{G}_m/k) \) does not give a functor \( \text{Hom}_{\text{PAb}_k}(\cdot, \mathbb{G}_m/k): \text{PAb}_k \to \text{Ab}^{\text{op}} \).

Nevertheless, it will essentially play a role of an inverse of \( \text{Hom}_{\text{Ab}}(\cdot, \mathbb{G}_m/k) \). Indeed, it is functorial in the sense that for any natural transformation \( F \) between multiplicative analytic groups \( \mathcal{G}_0 \) and \( \mathcal{G}_1 \) over \( k \), the map

\[
\text{Hom}_{\text{PAb}_k}(F, \mathbb{G}_m/k): \text{Hom}_{\text{PAb}_k}(\mathcal{G}_1, \mathbb{G}_m/k) \to \text{Hom}_{\text{PAb}_k}(\mathcal{G}_0, \mathbb{G}_m/k), \gamma \mapsto \gamma \circ F
\]

is a group homomorphism, and the correspondence \( F \mapsto \text{Hom}_{\text{PAb}_k}(F, \mathbb{G}_m/k) \) preserves identities and compositions.

Let \( G \) be a \( \mathcal{U} \)-small discrete Abelian group. For any \( g \in G \), \( \iota^d_G(g) \) is a group-like element of \( C_0(G, k) \) because \( \iota^d_G \) preserves the comultiplication, and hence \( \iota^d_G(g) \in \mathbb{G}_m/k(C_0(G, k)) \) yields a natural transformation \( \eta_{\text{Ab}}(G)(g): \text{Hom}_{\text{Ab}}(G, \mathbb{G}_m/k) \Rightarrow \mathbb{G}_m/k \) by Lemma 4.3 and Yoneda’s lemma.

**Lemma 4.6.** For any \( \mathcal{U} \)-small discrete Abelian group \( G \), the map

\[
\eta_{\text{Ab}}(G): G \to \text{Hom}_{\text{PAb}_k}(\text{Hom}_{\text{Ab}}(G, \mathbb{G}_m/k), \mathbb{G}_m/k)
\]

\[
g \mapsto \eta_{\text{Ab}}(G)(g)
\]

is a group isomorphism.

**Proof.** The map \( \eta_{\text{Ab}}(G) \) is a group homomorphism because the evaluation at \( C_0(G, k) \) preserves the multiplication by the definition of \( \text{Hom}_{\text{PAb}_k}(G, \mathbb{G}_m/k) \). For a Hopf monoid homomorphism \( \varphi: C_0(k) \to C_0(G, k) \), we denote by
F(ϕ) the natural transformation \( \mathcal{H} \text{om}_{\text{Ab}}(G, \mathbb{G}_{m/k}) \Rightarrow \mathbb{G}_{m/k} \) corresponding to \( \varphi \) by Lemma 4.3 and Corollary 4.4. The map

\[
F : \text{Hom}_{\text{Hopf}(\text{Ban}_c^{ur}(k), \mathbb{G}_{m/k})}(C_0(\mathbb{Z}, k), C_0(G, k))
\]

\[
\Rightarrow \text{Hom}_{\mathbb{P}_{\text{Ab}}(k)}(\mathcal{H} \text{om}_{\text{Ab}}(G, \mathbb{G}_{m/k}), \mathbb{G}_{m/k}), \varphi \mapsto F(\varphi)
\]

is bijective by Yoneda’s lemma. Put \( H := F^{-1} \circ \eta_{\text{Ab}}(G) \). It suffices to verify the bijectivity of \( H \).

We have \( H(g)(f) = \sum_{n \in \mathbb{Z}} f(n) \iota_G^d(g)^n \) for any \( (g, f) \in G \times C_0(\mathbb{Z}, k) \) by the construction. In particular, we obtain \( H(g)(\iota_Z^d(1)) = \iota_G^d(g) \) for any \( g \in G \times C_0(\mathbb{Z}, k) \). Therefore the injectivity of \( \iota_G^d \) implies that of \( H \). We show the surjectivity of \( H \). Let \( \varphi \) be a Hopf monoid homomorphism \( C_0(\mathbb{Z}, k) \rightarrow C_0(G, k) \). Since \( \iota_Z^d(1) \) is a group-like element of \( C_0(\mathbb{Z}, k) \), \( \varphi(\iota_Z^d(1)) \) is a group-like element of \( C_0(G, k) \). Therefore we have

\[
\sum_{g \in G} \varphi(\iota_Z^d(1)) \iota_G^d(g) \iota_G^d(g) = \varphi(\iota_Z^d(1)) \iota_G^d(g)
\]

\[
= \sum_{(g_0, g_1) \in G^2} \varphi(\iota_Z^d(1))(g_0) \varphi(\iota_Z^d(1))(g_1) \iota_G^d(g_0) \iota_G^d(g_1)
\]

in \( C_0(G, k) \otimes_k C(G, k) \) for any \( (g_0, g_1) \in G^2 \). It implies that there is at most one \( g \in G \) satisfying \( \varphi(\iota_Z^d(1))(g) \neq 0 \) by Proposition 2.6, and such a \( g \) satisfies \( \varphi(\iota_Z^d(1))(g)^2 = \varphi(\iota_Z^d(1))(g) \), that is, \( \varphi(\iota_Z^d(1))(g) = 1 \). By \( \varphi(\iota_Z^d(1)) \in C_0(G, k)^\times \), it implies that there is a \( g \in G \) such that \( \varphi(\iota_Z^d(1)) = \iota_G^d(g) \). For any \( f \in C_0(\mathbb{Z}, k) \), we have \( H(g)(f) = \sum_{n \in \mathbb{Z}} f(n) \iota_G^d(g)^n = \sum_{n \in \mathbb{Z}} f(n) \varphi(\iota_Z^d(1))^n = \varphi(f) \). It implies \( \varphi = H(g) \). Therefore \( H \) is surjective. \( \square \)

**Lemma 4.7.** For any multiplicative Abelian group \( \mathcal{G} \) over \( k \), there is a \( \mathcal{W} \)-small Abelian group \( G \) such that \( \mathcal{H} \text{om}_{\text{Ab}}(G, \mathbb{G}_{m/k}) \) is isomorphic to \( \mathcal{G} \).

**Proof.** Since \( \mathcal{G} \) is a multiplicative analytic group over \( k \), there is a tuple \( (I, J, F, H) \) of \( \mathcal{W} \)-small sets \( I \) and \( J \) and natural transformations \( F : \mathbb{G}_{m/k} \rightarrow \mathbb{G}_{m/k} \) and \( H : \mathcal{G} \rightarrow \mathbb{G}_{m/k} \) such that \( (\mathcal{G}, H) \) satisfies the universality of the kernel of \( F \). By Corollary 4.4 and Lemma 4.6, there is a unique group homomorphism

\[
\varphi : \mathbb{Z}^{\oplus J} \rightarrow \mathbb{Z}^{\oplus I}
\]

such that \( \eta_{\text{Ab}}(\mathbb{Z}^{\oplus I}) \circ \varphi = \mathcal{H} \text{om}_{\text{Ab}}(\mathcal{H} \text{om}_{\mathbb{P}_{\text{Ab}}(k)}(F, \mathbb{G}_{m/k}), \mathbb{G}_{m/k}) \circ \eta_{\text{Ab}}(\mathbb{Z}^{\oplus J}) \).

Put \( G := \text{coker}(\varphi) \). Since \( G \) is a quotient of \( \mathbb{Z}^{\oplus I} \), \( G \) is \( \mathcal{W} \)-small. We
denote by $\pi$ the canonical projection $\mathbb{Z} \oplus I \twoheadrightarrow G$. By the left exactness of the functor $\mathcal{H}om_{Ab}(\bullet, A_{\mathbb{G}_{m/k}}) : \text{Ab}^{\text{op}} \to \text{Ab}$ for any commutative monoid object $A$ in $(\text{Banur} \leq (k), \hat{\otimes}_k, k)$, $(\mathcal{H}om_{Ab}(G, \mathbb{G}_{m/k}), \mathcal{H}om_{Ab}(\pi, \mathbb{G}_{m/k}))$ satisfies the universality of the kernel of $F$ identified with $\mathcal{H}om_{PAb}(\varphi, \mathbb{G}_{m/k})$ through the natural isomorphisms $\mathcal{H}om_{Ab}(\mathbb{Z} \oplus I, \mathbb{G}_{m/k}) \Rightarrow \mathbb{G}_{m/k}$ and $\mathcal{H}om_{Ab}(\mathbb{Z} \oplus J, \mathbb{G}_{m/k}) \Rightarrow \mathbb{G}_{m/k}$.

Thus $G$ is naturally isomorphic to $\mathcal{H}om_{Ab}(G, \mathbb{G}_{m/k})$.

By Lemma 4.3, Lemma 4.6, and Lemma 4.7, we obtain the following:

**Corollary 4.8.** Every multiplicative analytic group $\mathcal{G}$ over $k$ is representable by $C_0(G, k)$ for a $\mathcal{U}$-small Abelian group $G$ isomorphic to $\mathcal{H}om_{PAb}(\varphi, \mathbb{G}_{m/k})$.

**Proof of Theorem 4.5.** The fullness and faithfulness immediately follow from Lemma 4.6. The essential surjectivity precisely coincides with the assertion of Lemma 4.7.

By Theorem 4.5, we obtain the following:

**Corollary 4.9.** The category $PAb_k$ forms an Abelian category with respect to a natural $\text{Ab}$-enrichment, and admits all $\mathcal{U}$-small colimits and all $\mathcal{U}$-small limits.

**Remark 4.10.** The functor $C_0(\bullet, k) : \text{Ab} \to \text{Hopf}(\text{Banur} \leq (k), \hat{\otimes}_k, k)$ does not preserve $\mathcal{U}$-small limits. For example, the limit of $(\mathbb{Z}/n\mathbb{Z})_{n \in \mathbb{N}\setminus\{0\}}$ in $\text{Ab}$ with respect to the canonical projections is $\mathbb{Z}$ equipped with the discrete topology, while the colimit of $(\mu_{n/k})_{n \in \mathbb{N}\setminus\{0\}} \cong (\mathcal{H}om_{Ab}(\mathbb{Z}/n\mathbb{Z}, \mathbb{G}_{m/k}))_{n \in \mathbb{N}\setminus\{0\}}$ in $PAb_k$ is the functor $\mu_{\infty/k} : \text{CAlg}(k) \to \text{Ab}$ which assigns the torsion group of $A_{\mathbb{G}_{m/k}}$ to each commutative monoid object $A$ in $(\text{Banur}(k), \hat{\otimes}_k, k)$. The natural transformation $\mu_{\infty/k} \Rightarrow \mathcal{H}om_{Ab}(\mathbb{Z}, \mathbb{G}_{m/k})$ given by the universality of the colimit $(\mu_{n/k})_{n \in \mathbb{N}\setminus\{0\}}$ is not a natural isomorphism, because $\iota^{\mathbb{Z}}_{\mathbb{Z}} : \mathbb{Z} \hookrightarrow C_0(\mathbb{Z}, k)_{\mathbb{G}_{m/k}}$ assigns to $1 \in \mathbb{Z}$ a $\mathbb{Z}$-torsionfree element. It implies that $\mu_{\infty/k}$ is not a multiplicative analytic group over $k$ and does not admit a maximal multiplicative analytic subgroup over $k$. 

\[ \vdash \]
4.2 Profinite Abelian group Let $A$ be a compact Hausdorff flat linear topological $O_k$-algebra. Then $A^\times \subset A$ is the intersection of the preimages of the multiplicative groups of finite quotients, and hence is a closed subset. Therefore it forms a profinite group. We denote by $A^{G_m/O_k}$ the discrete group which shares the underlying group with $A^\times$.

The correspondence $A \rightsquigarrow A^{G_m/O_k}$ restricted to $\mathcal{U}$ gives a functor $\mathbb{G}_m/O_k : \text{CAlg}(O_k) \to \text{Ab}$, which is a formal geometric counterpart of $S^1$.

For any $\mathcal{U}$-small set $I$, the correspondence $A \rightsquigarrow (A^{G_m/O_k})^I$ restricted to $\mathcal{U}$ gives a functor $\mathbb{G}_m^I/O_k : \text{CAlg}(O_k) \to \text{Ab}$. A functor $\mathcal{G} : \text{CAlg}(O_k) \to \text{Ab}$ is said to be a torus if it is naturally isomorphic to $\mathbb{G}_m^I/O_k$ for some $\mathcal{U}$-small set $I$, and is said to be a multiplicative formal group over $O_k$ if it is naturally isomorphic to the kernel of a natural transformation between tori.

We establish a $p$-adic Pontryagin duality between profinite Abelian groups and multiplicative formal groups over $O_k$ in a parallel way to the $p$-adic Pontryagin duality in §4.1.

Example 4.11. (i) Let $n \in \mathbb{N} \setminus \{0\}$. For a compact Hausdorff flat linear topological $O_k$-algebra $A$, we denote by $A^{\mu_n/O_k} \subset A^{G_m/O_k}$ the subgroup \{ $f \in A^{G_m/O_k} \mid f^n = 1$ \}. The correspondence $A \rightsquigarrow A^{\mu_n/O_k}$ restricted to $\mathcal{U}$ gives a functor $\mu_n/O_k : \text{CAlg}(O_k) \to \text{Ab}$, which is a multiplicative formal group over $O_k$ by a completely similar argument in Example 4.1 (i).

(ii) Let $D_{\mathbb{N}}$ denote the set introduced in Example 4.1 (ii). For a compact Hausdorff flat linear topological $O_k$-algebra $A$, we denote by $A^{\hat{\mathbb{Z}}(1)/O_k}$ the inverse limit of $(A^{\mu_n/O_k})_{n \in \mathbb{N} \setminus \{0\}}$ with respect to the system of $n_0^{-1}n_1$-th powers $A^{\mu_{n_1}/O_k} \to A^{\mu_{n_0}/O_k}$ indexed by $(n_0, n_1) \in D_{\mathbb{N}}$ equipped with the discrete topology. The correspondence $A \rightsquigarrow A^{\hat{\mathbb{Z}}(1)/O_k}$ restricted to $\mathcal{U}$ gives a functor $\hat{\mathbb{Z}}(1)/O_k : \text{CAlg}(O_k) \to \text{Ab}$, which is a multiplicative formal group over $O_k$ by a completely similar argument in Example 4.1 (ii).

For profinite Abelian groups $G$ and $H$, we denote by $\mathcal{H}\text{om}_{\text{PAb}}(G, H)$ the discrete Abelian group whose underlying set is the set of continuous group homomorphisms $G \to H$ and whose operation is the pointwise multiplication. Let $G$ be a $\mathcal{U}$-small profinite Abelian group. The correspondence $A \rightsquigarrow \mathcal{H}\text{om}_{\text{PAb}}(G, A^\times)$ restricted to $\mathcal{U}$ gives a functor

$$\mathcal{H}\text{om}_{\text{PAb}}(G, G_m/O_k) : \text{CAlg}(O_k) \to \text{Ab}.$$
We note that this convention is misleading because $\text{Hom}_{\text{PAb}}(G, G_{m/O_k})$ is not a functor which assigns the discrete Abelian group of continuous group homomorphism $G \to A^G_{m/O_k}$ to each commutative monoid object $A$ in $(\mathcal{C}_{ch}, \otimes_{O_k}, O_k)$, but employ it in order to formulate a $p$-adic Pontryagin duality in a parallel way to the $p$-adic Pontryagin duality in §4.1. Since $G_{m/O_k}$ is a counterpart of $S^1$, $\text{Hom}_{\text{PAb}}(\bullet, G_{m/O_k})$ is a $p$-adic analogue of the Pontryagin dual.

**Proposition 4.12.** For any $\mathcal{U}$-small profinite Abelian group $G$,

$$\mathcal{H}\text{om}_{\text{PAb}}(G, G_{m/O_k})$$

forms a multiplicative formal group over $O_k$.

In order to verify Proposition 4.12, we prepare several lemmata.

**Lemma 4.13.** For any $\mathcal{U}$-small profinite Abelian group $G$,

$$\mathcal{H}\text{om}_{\text{PAb}}(G, G_{m/O_k})$$

is representable by $O_k[[G]]$.

**Proof.** By Proposition 3.7 (i), $O_k[[G]]$ represents a functor $\hat{G} : \text{CAlg}(O_k) \to \text{Ab}$. Denote by $u \in \mathcal{H}\text{om}_{\text{PAb}}(G, O_k[[G]]^\times)$ the composite of the canonical embedding $G \hookrightarrow O_k[G]$ and $i_C^G$, and by $F$ the natural transformation $\hat{G} \Rightarrow \mathcal{H}\text{om}_{\text{PAb}}(G, G_{m/O_k})$ determined by the equality $F(O_k[[G]])(\text{id}_{O_k[[G]]}) = u$ by Yoneda’s lemma because $u$ is a continuous group homomorphism. For any $\mathcal{U}$-small commutative monoid object $A$ in $(\mathcal{C}_{ch}, \otimes_{O_k}, O_k)$, $F(A)$ is the map $\text{Hom}_{\text{CAlg}(O_k)}(O_k[[G]], A) \to \mathcal{H}\text{om}_{\text{PAb}}(G, A^\times)$, $\varphi \mapsto \varphi \circ u$, which is bijective by the universality of the Iwasawa algebra. Therefore $F$ is a natural equivalence. \qed

Let $I$ be a set. We denote by $\hat{Z}^\oplus I$ the profinite completion of the direct sum $\hat{Z}^\oplus I$ of $I$-copies of the underlying discrete group of $\hat{Z}$. For each $i \in I$, we denote by $\iota_{I,i} : \hat{Z} \to \hat{Z}^\oplus I$ the composite of the $i$-th canonical embedding $\hat{Z} \hookrightarrow \hat{Z}^\oplus I$ and the canonical embedding $\hat{Z}^\oplus I \hookrightarrow \hat{Z}^\oplus I$.

**Lemma 4.14.** Let $I$ be a set. For any profinite group $G$, the map

$$\mathcal{H}\text{om}_{\text{PAb}}(\hat{Z}^\oplus I, G) \to G^I, \chi \mapsto (\chi(\iota_{I,i}(1)))_{i \in I}$$

is a group isomorphism, where $G^I$ is equipped with the pointwise multiplication.
Proof. Since every subgroup of $\hat{\mathbb{Z}}$ of finite index is closed, $\iota_{I,i}$ is continuous for any $i \in I$. Therefore the assertion immediately follows from the universality of the completion and the direct sum, because the forgetful functor $\text{PAb} \to \text{Ab}$ is represented by $\hat{\mathbb{Z}}$.

**Corollary 4.15.** For any $\mathcal{U}$-small set $I$, $\mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}}$ is representable by $O_k[[\hat{\mathbb{Z}}^{\oplus I}]]$.

Proof. The assertion immediately follows from Lemma 4.13 applied to the case $G = \hat{\mathbb{Z}}^{\oplus I}$ and Lemma 4.14.

**Proof of Proposition 4.12.** For a set $I$ and a profinite group $H$, denote by $\varphi_{I,H}$ the group isomorphism $\mathcal{H}om_{\text{PAb}}(\hat{\mathbb{Z}}^{\oplus I}, H) \to H^I$ in Lemma 4.14. Denote by $\varphi_0$ the group homomorphism $\varphi_{G,G}^{-1}(\text{id}_G) : \hat{\mathbb{Z}}^{\oplus G} \to G$, and by $\varphi_1$ the composite of the group homomorphism $\varphi_{\ker(\varphi),\ker(\varphi)} : \hat{\mathbb{Z}}^{\oplus \ker(\varphi)} \to \ker(\varphi)$ and the inclusion $\ker(\varphi_0) \hookrightarrow \hat{\mathbb{Z}}^{\oplus G}$. By Proposition 3.7 (i),

$$O_k[[\varphi_0]] : O_k[[\hat{\mathbb{Z}}^{\oplus G}]] \to O_k[[G]]$$

and $O_k[[\varphi_1]] : O_k[[\hat{\mathbb{Z}}^{\oplus \ker(\varphi_0)}]] \to O_k[[\hat{\mathbb{Z}}^{\oplus G}]]$ form Hopf monoid homomorphisms. By Lemma 4.13 and Corollary 4.15, they induce natural transformations $F_0 : \mathcal{H}om_{\text{PAb}}(G, \mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}}) \Rightarrow \mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}}$ and $F_1 : \mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}} \Rightarrow \mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}}$. Since $\varphi_0$ is a continuous surjective group homomorphism between compact Hausdorff topological groups, $\ker(\varphi_0) \subset \hat{\mathbb{Z}}^{\oplus G}$ is closed and the group isomorphism $\hat{\mathbb{Z}}^{\oplus G}/\ker(\varphi_0) \to G$ induced by $\varphi_0$ is a homeomorphism. Therefore $(\mathcal{H}om_{\text{PAb}}(G, \mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}}), F_0)$ satisfies the universality of the kernel of $F_1$ by a completely similar argument in the second paragraph in the proof of Proposition 4.2.

We denote by $\text{Ab}_{O_k}$ the category of multiplicative formal groups over $O_k$ and natural transformations. By Proposition 4.12, the correspondence $G \mapsto \mathcal{H}om_{\text{PAb}}(G, \mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}})$ gives a functor $\mathcal{H}om_{\text{PAb}}(\bullet, \mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}}) : \text{PAb}^{\text{op}} \to \text{Ab}_{O_k}$. Now we state a $p$-adic analogue of the Pontryagin duality.

**Theorem 4.16.** The functor $\mathcal{H}om_{\text{PAb}}(\bullet, \mathbb{G}_m^{I}_{\mathbb{Q}/\mathbb{K}})$ is fully faithful and essentially surjective.

By the axiom of choice and the smallness of PAb, Theorem 4.16 implies that PAb$^{\text{op}}$ is naturally equivalent to Ab$_{O_k}$, but there is an issue on an
inverse similar to that for $\text{Hom}_{\text{Ab}}(\bullet, \mathbb{G}_m/\mathbb{G}_{m/k})$. Although the fullness and the faithfulness immediately follows from the proof of Corollary 3.8 (i) because the Berkovich spectrum of $C(G, k)$ is canonically homeomorphic to $G$ by [1] 9.2.7 Corollary, we give an alternative proof constructing an “inverse correspondence”. For this purpose, we prepare several notions and lemmata.

Let $G$ be a multiplicative formal group over $O_k$. We denote by $\text{Hom}_{\text{Ab}}(G, \mathbb{G}_m/O_k)$ the set equipped with the pointwise multiplication and the topology generated by all subsets of the form $\{g \in \text{Hom}_{\text{Ab}}(G, \mathbb{G}_m/O_k) \mid g(A)(\varphi) \in U\}$ for some tuple $(A, \varphi, U)$ of a commutative monoid object $A$ in $(\mathcal{C}_\text{ch}, \hat{\otimes}_{O_k}, O_k)$, a $\varphi \in G(A)$, and an open subset $U \subset A$. It actually forms a topological group by the definition of the pointwise multiplication. By a reason similar to that for $\text{Hom}_{\text{PAb}}(\bullet, \mathbb{G}_m/k)$, the correspondence $G \mapsto \text{Hom}_{\text{Ab}}(G, \mathbb{G}_m/O_k)$ does not give a functor $\text{Hom}_{\text{Ab}}(\bullet, \mathbb{G}_m/O_k): \text{Ab}_{O_k} \to \text{Ab}_{op}$, but is functorial in the sense that for any natural transformation $F$ between multiplicative formal groups $G_0$ and $G_1$ over $O_k$, the map

$$\text{Hom}_{\text{Ab}}(F, \mathbb{G}_m/O_k): \text{Hom}_{\text{Ab}}(G_1, \mathbb{G}_m/O_k) \to \text{Hom}_{\text{Ab}}(G_0, \mathbb{G}_m/O_k), \gamma \mapsto \gamma \circ F$$

is a group homomorphism, and the correspondence $F \mapsto \text{Hom}_{\text{Ab}}(F, \mathbb{G}_m/O_k)$ preserves identities and compositions.

Let $G$ be a $\mathcal{U}$-small profinite Abelian group. For any $g \in G$, $\iota_G^\mathcal{U}(g)$ is a group-like element of $O_k[[G]]$ because $g$ is a group-like element of $O_k[G]$, and hence $\iota_G^\mathcal{U}(g) \in O_k[[G]]^\times$ determines a natural transformation $\eta_{\text{PAb}}(G)(g): \text{Hom}_{\text{PAb}}(G, \mathbb{G}_m/O_k) \Rightarrow \mathbb{G}_m/O_k$ by Lemma 4.13 and Yoneda’s lemma.

**Lemma 4.17.** For any $\mathcal{U}$-small profinite Abelian group $G$, the map

$$\eta_{\text{PAb}}(G): G \to \text{Hom}_{\text{Ab}}(\text{Hom}_{\text{PAb}}(G, \mathbb{G}_m/O_k), \mathbb{G}_m/O_k)$$

$$\quad g \mapsto \eta_{\text{PAb}}(G)(g)$$

is a homeomorphic group isomorphism.
Proof. The map $\eta_{P\text{Ab}}(G)$ is a group homomorphism because the evaluation at $O_k[[G]]$ preserves the multiplication by the definition of $\mathcal{H}\text{om}_{A\text{b}O_k}(G, \mathbb{G}_{m/O_k})$. For any pair $(A, \varphi)$ of a commutative monoid object $A$ in $((\mathcal{C}_f^{ch}, \otimes_{O_k}, O_k)$ and a $\varphi \in \mathcal{H}\text{om}_{A\text{b}}(G, A^\times)$, $\varphi$ corresponds to a continuous $O_k$-algebra homomorphism $\tilde{\varphi} : O_k[[G]] \to A$ by Lemma 4.13, and the preimage of the open subset $\{g \in \text{Hom}_{A\text{b}O_k}(G, \mathbb{G}_{m/O_k}, \mathbb{G}_{m/O_k}) \mid g(A)(\varphi) \in U\}$ by $\eta_{P\text{Ab}}(G)$ coincides with $\{g \in G \mid \eta_{P\text{Ab}}(G)(g)(\varphi) \in U\} = \{g \in G \mid \tilde{\varphi}(\iota_G^c(g)) \in U\}$, which is open by the continuity of $\tilde{\varphi}$ and $\iota_G^c$, for any open subset $U \subset A$. Therefore $\eta_{A\text{b}}(G)$ is continuous.

For a Hopf monoid homomorphism $\varphi : O_k[[\hat{Z}]] \to O_k[[G]]$, we denote by $F(\varphi)$ the natural transformation $\mathcal{H}\text{om}_{A\text{b}O_k}(G, \mathbb{G}_{m/O_k}) \to \mathbb{G}_{m/O_k}$ corresponding to $\varphi$ by Lemma 4.13 and Corollary 4.15. The map

$$F : \text{Hom}_{\text{Hopf}(\mathcal{C}_f^{ch}, \otimes_{O_k}, O_k)}(O_k[[\hat{Z}]], O_k[[G]]) \to \text{Hom}_{A\text{b}O_k}(\mathcal{H}\text{om}_{A\text{b}}(G, \mathbb{G}_{m/O_k}), \mathbb{G}_{m/O_k})$$

$$\varphi \mapsto F(\varphi)$$

is bijective by Yoneda’s lemma. Put $H := F^{-1} \circ \eta_{P\text{Ab}}(G)$. It suffices to verify the bijectivity of $H$. We have $H(g)(\iota^c_{\hat{Z}}(n)) = \iota^c_G(g)^n$ for any $(g, n) \in G \times \mathbb{Z}$ by the construction. In particular, we obtain $H(g)(\iota^c_{\hat{Z}}(1)) = \iota^c_G(g)$ for any $g \in G \times O_k[[\hat{Z}]]$. Therefore the injectivity of $\iota^c_G$ implies that of $H$.

We show the surjectivity of $H$. Let $\varphi$ be a Hopf monoid homomorphism $O_k[[\hat{Z}]] \to O_k[[G]]$. Since $\iota^c_{\hat{Z}}(1)$ is a group-like element of $O_k[[\hat{Z}]]$, $\varphi(\iota^c_{\hat{Z}}(1))$ is a group-like element of $O_k[[G]]$. Let $G_0 \subset G$ be an open subgroup. Denote by $\pi_{G_0} : O_k[[G]] \to O_k[[G/G_0]]$ the canonical projection. Then $\pi_{G_0}(\varphi(\iota^c_{\hat{Z}}(1)))$ is a group-like element of $O_k[G/G_0]$, and hence there is a unique $g_{G_0} \in G/G_0$ such that $\pi_{G_0}(\varphi(\iota^c_{\hat{Z}}(1))) = \iota^c_{G/G_0}(g_{G_0})$. By the uniqueness, $(g_{G_0}G_0)_{G_0}$ forms an element of the profinite completion of $G$, and hence corresponds to a unique $g \in G$. It implies $\varphi(\iota^c_{\hat{Z}}(1)) = \iota^c_G(g)$. For any $n \in \mathbb{Z}$, we have $H(g)(\iota^c_{\hat{Z}}(n)) = \iota^c_G(g)^n = \varphi(\iota^c_{\hat{Z}}(1))^n = \varphi(\iota^c_{\hat{Z}}(n))$. It implies $\varphi = H(g)$ because the image of $\mathbb{Z}$ is dense in $\hat{Z}$. Therefore $H$ is surjective.

For any open subgroup $G_0 \subset G$, the composite of $\iota^c_G$ and $\pi_{G_0}$ gives a continuous group homomorphism $\varphi : G \to O_k[[G/G_0]]^\times$, and the image of $G_0$ by $H$ coincides with the open subset

$$\{g \in \text{Hom}_{A\text{b}O_k}(\mathcal{H}\text{om}_{A\text{b}}(G, \mathbb{G}_{m/O_k}), \mathbb{G}_{m/O_k}) \mid g(O_k[[G/G_0]])(\varphi) \in O_k \iota^c_{G/G_0}(1)\}$$

by $\varphi(g) = \pi_{G_0}(\iota^c_G(g)) = \iota^c_{G/G_0}(g_{G_0})$. Therefore $H$ is open. \qed
Lemma 4.18. For any multiplicative formal group $\mathcal{G}$ over $O_k$, there is a $\mathcal{U}$-small profinite Abelian group $G$ such that $\text{Hom}_{\text{PAb}}(G, \mathbb{G}_{m/O_k})$ is isomorphic to $\mathcal{G}$.

Proof. The assertion follows from a completely parallel argument in the proof of Lemma 4.7 by Corollary 4.15 and Lemma 4.17.

By Lemma 4.13, Lemma 4.17, and Lemma 4.18, we obtain the following:

Corollary 4.19. Every multiplicative formal group $\mathcal{G}$ over $O_k$ is representable by $O_k[[G]]$ for a $\mathcal{U}$-small profinite Abelian group $G$ isomorphic to $\text{Hom}_{\text{Ab}_{O_k}}(\mathcal{G}, \mathbb{G}_{m/O_k})$.

Proof of Theorem 4.16. The fullness and faithfulness immediately follow from Lemma 4.17. The essential surjectivity precisely coincides with the assertion of Lemma 4.18.

Corollary 4.20. The category $\text{Ab}_{O_k}$ forms an Abelian category with respect to a natural Ab-enrichment, and admits all $\mathcal{U}$-small colimits and all $\mathcal{U}$-small limits.

Proof. By Theorem 4.16 and the classical Pontryagin duality, the assertion immediately follows from the elementary fact that the full subcategory of $\text{Ab}$ consisting of $\mathcal{U}$-small torsion Abelian groups admits all $\mathcal{U}$-small colimits and all $\mathcal{U}$-small limits.

Remark 4.21. The functor $O_k[[\bullet]]: \text{PAb} \to \text{Hopf}((\mathcal{C}^{\text{ch}}_{\mathfrak{f}}, \hat{\otimes}_{O_k}, O_k)$ preserves $\mathcal{U}$-small limits unlike $C_0(\bullet, k)$ (cf. Remark 4.10). Therefore for any functor $\mathcal{G}: \text{CAlg}(O_k) \to \text{Grp}$, the set $\Sigma$ of multiplicative formal subgroups of $\mathcal{G}$ over $O_k$ forms a partially ordered set with respect to inclusions, which corresponds to a $\mathcal{U}$-small diagram in $\text{PAb}$ by Theorem 4.16, and the image of its limit in $\text{PAb}$ by $O_k[[\bullet]]$ gives a Hopf monoid in $(\mathcal{C}^{\text{ch}}_{\mathfrak{f}}, \hat{\otimes}_{O_k}, O_k)$, which represents a multiplicative formal subgroup of $\mathcal{G}$ over $O_k$ satisfying the universality of the colimit of $\Sigma$. It implies that $\mathcal{G}$ admits a unique maximal multiplicative formal subgroup over $O_k$.

Following the traditional convention of a representation of an algebraic group, we define the notion of a representation of formal group schemes of a certain type. Let $\mathcal{G}$ be a functor $\text{CAlg}(O_k) \to \text{Grp}$ represented by a
commutative Hopf monoid object $A$ in $(\mathcal{C}_{\text{fl}}^{\text{ch}}, \hat{\otimes}O_k, O_k)$. A representation of $\mathcal{G}$ is a right $A$-comodule object in $(\mathcal{C}_{\text{fl}}^{\text{ch}}, \hat{\otimes}O_k, O_k)$. A representation of $\mathcal{G}$ is said to be irreducible if it admits precisely two quotients as representations of $\mathcal{G}$. By Theorem 3.2, the irreducibility of a representation of $\mathcal{G}$ is equivalent to the irreducibility of its dual as a Banach left $A_{\text{fl}}^{\text{ch}}$-module in the sense that it admits precisely two closed $A_{\text{fl}}^{\text{ch}}$-submodules.

The left regular $A_{\text{fl}}^{\text{ch}}$-module forms a “universal family” of irreducible unitary Banach $k$-linear representations of the discrete group $\mathcal{G}(O_k)$ in the sense that for any irreducible unitary Banach $k$-linear representation $V$ of $\mathcal{G}(O_k)$ which is “analytic” in the sense that it admits a continuous $O_k$-linear homomorphism $\rho: V_{\text{Ban}}^{\text{ur}} \to V_{\text{Ban}}^{\text{ur}} \hat{\otimes}O_k A$ for which $V_{\text{Ban}}^{\text{ur}}$ forms a representation of $\mathcal{G}$ such that $(\text{id}_{V_{\text{Ban}}^{\text{ur}}} \otimes g)(\rho(\mu))(v) = \mu(gv)$ for any $(g,\mu,v) \in \mathcal{G}(O_k) \times V_{\text{Ban}}^{\text{ur}} \times V$, there is a submetric $k$-linear homomorphism $\pi: A_{\text{fl}}^{\text{ch}} \to V$ with dense image such that $g\pi(1) = \pi(g)$ for any $g \in \mathcal{G}(O_k) = \text{Hom}_{\text{CAlg}(O_k)}(A, O_k) \subset A_{\text{fl}}^{\text{ch}}$.

Let $\mathcal{G}$ be a multiplicative formal group over $O_k$. By Corollary 4.19, $\mathcal{G}$ is represented by a commutative Hopf monoid object $A$ in $(\mathcal{C}_{\text{fl}}^{\text{ch}}, \hat{\otimes}O_k, O_k)$. Therefore the notion of a representation of $\mathcal{G}$ makes sense as long as we fix $A$, which is unique up to Hopf monoid isomorphism. At least, the following holds for any choice of such an $A$:

**Theorem 4.22.** Every representation of a multiplicative formal group $\mathcal{G}$ finitely generated over $O_k$ is completely reducible, that is, admits a homeomorphic $O_k$-linear isomorphism to the direct product of finitely many irreducible representations preserving the action of $\mathcal{G}$.

**Proof.** By Corollary 4.19, there is a $\mathcal{U}$-small profinite Abelian group $G$ such that $\mathcal{G}$ is represented by $O_k[[G]]$. It suffices to show that every $O_k[[G]]$-comodule object in $(\mathcal{C}_{\text{fl}}^{\text{ch}}, \hat{\otimes}O_k, O_k)$ admits a $O_k[[G]]$-comodule isomorphism to the direct product of finitely many $O_k[[G]]$-comodule objects in $(\mathcal{C}_{\text{fl}}^{\text{ch}}, \hat{\otimes}O_k, O_k)$ admitting precisely two quotients as $O_k[[G]]$-subcomodule objects in $(\mathcal{C}_{\text{fl}}^{\text{ch}}, \hat{\otimes}O_k, O_k)$. By Theorem 3.2, it suffices to show that every $C(G,k)$-module object $V$ in $(\text{Ban}_{\leq}^{\text{ur}}(k), \hat{\otimes}k, k)$ of finite dimension admits a $C(G,k)$-module isomorphism to the direct sum of finitely many irreducible $C(G,k)$-module objects in $(\text{Ban}_{\leq}^{\text{ur}}(k), \hat{\otimes}k, k)$. It immediately follows from the fact that idempotents generates a dense $k$-subalgebra of $C(G,k)$. $\square$
4.3 Fourier transform We denote by $A^1_{O_k}$ the forgetful functor $\text{CAlg}(O_k) \to \text{Set}$. For a functor $\mathcal{X} : \text{CAlg}(O_k) \to \text{Set}$, we denote by $H^0(\mathcal{X}, A^1_{O_k})$ the set of natural transformations $\mathcal{X} \Rightarrow A^1_{O_k}$ equipped with the pointwise $O_k$-algebra structure. When $\mathcal{X}$ is representable by a commutative monoid object $A$ in $(\mathbb{C}_{\text{fl}}^\text{ch}, \hat{\otimes}_{O_k}, O_k)$, then $H^0(\mathcal{X}, A^1_{O_k})$ is naturally isomorphic to the underlying $O_k$-algebra of $A$. Therefore if $\mathcal{X}$ is an affine formal scheme over $\text{Spf}(O_k)$ represented by a commutative compact Hausdorff flat linear topological $O_k$-algebra, then $H^0(\mathcal{X}, A^1_{O_k})$ can be regarded as the underlying $O_k$-algebra of global sections. Therefore $H^0(\mathcal{X}, A^1_{O_k})$ is a generalised notion of a ring of functions on $\mathcal{X}$.

Let $G$ be a $\mathcal{U}$-small profinite Abelian group. We denote by $\hat{G}$ the composite of $\mathcal{H}\text{om}_{\text{PAb}}(G, G_m/O_k)$ and the forgetful functor $\text{Ab} \to \text{Set}$. Let $f \in C(G, k)^{\text{D}_{\text{ban}}}$. For a commutative monoid object $A$ in $(\mathbb{C}_{\text{fl}}^\text{ch}, \hat{\otimes}_{O_k}, O_k)$, we denote by $\hat{f}(A) : \hat{G}(A) \to A$ the group homomorphism which assigns to each $\chi \in \hat{G}(A) = \mathcal{H}\text{om}_{\text{PAb}}(G, A^\times)$ a unique $h \in A$ satisfying $f(\mu \circ \chi) = \mu(h)$ for any $\mu \in A^{\text{D}_{\text{fl}}}$, which exists by the bijectivity of $\eta_{\text{fl}}^\text{ch}(A) : A \to A^{\text{D}_{\text{fl}}}$, $\gamma \mapsto \hat{\gamma}$. The correspondence $A \sim \hat{f}(A)$ gives a natural transformation $\hat{f} : \hat{G} \Rightarrow A^1_{O_k}$. We denote by $\mathcal{F}_G$ the ring homomorphism $C(G, k)^{\text{D}_{\text{ban}}} \to H^0(\hat{G}, A^1_{O_k})$, $f \mapsto \hat{f}$. It gives a nontrivial conversion connecting two function rings $C(G, k)$ and $H^0(\hat{G}, A^1_{O_k})$, and is a $p$-adic analogue of Fourier transform. We note that we do not need to take the first dual in the Archimedean setting, because every Hilbert space admits a canonical isomorphism to its first dual. We show a counterpart of Plancherel’s theorem.

**Theorem 4.23.** For any $\mathcal{U}$-small profinite Abelian group $G$, $\mathcal{F}_G$ is a ring isomorphism.

**Proof.** We denote by $\delta : G \to C(G, k)^{\text{D}_{\text{ban}}}$ the map which assigns the delta function $\delta_g : C(G, k) \to k$, $f \mapsto f(g)$ concentrated at $g$ to each $g \in G$. The assertion immediately follows from the fact that the map $H^0(\hat{G}, A^1_{O_k}) \to C(G, k)^{\text{D}_{\text{ban}}}$ which assigns to each natural transformation $h : \hat{G} \Rightarrow A^1_{O_k}$ the submetric $k$-linear homomorphism $C(G, k) \to k$, $f \mapsto h(C(G, k)^{\text{D}_{\text{ban}}})(\delta)(f)$ gives the inverse transform by the construction. □

We explain the relation to Iwasawa theory. For this purpose, we recall several classical notions. The group homomorphism $\mathbb{Z} \to O_k[[T]]^\times$, $c \mapsto (1 + T)^c$ extends to a unique continuous group homomorphism $\mathbb{Z}_p \to O_k[[T]]^\times$, etc. Therefore the determinant of the natural transformation $\delta : \hat{G} \Rightarrow A^1_{O_k}$ is given by

$$\det(\langle \hat{f}(g) \rangle) = \prod_{\chi \in \hat{G}} \text{det}(\chi)^{\chi(g)}.$$
which extends to a unique continuous $O_k$-algebra homomorphism $O_k[[\mathbb{Z}_p]] \to O_k[[T]]$ by the universality of Iwasawa algebra through $\iota_{\mathbb{Z}_p}^*$, which is a homeomorphic isomorphism and is called Iwasawa’s isomorphism. The evaluation map $C(\mathbb{Z}_p, k) \times \mathbb{Z}_p \to k$ extends to a unique continuous $O_k$-bilinear pairing $C(\mathbb{Z}_p, k) \times O_k[[\mathbb{Z}_p]] \to k$, which induces a homeomorphic $O_k$-algebra isomorphism $O_k[[\mathbb{Z}_p]] \to C(\mathbb{Z}_p, k)^{\text{Ban}}$. Combining these two homeomorphic $O_k$-algebra isomorphisms, we obtain a homeomorphic $O_k$-algebra isomorphism $C(\mathbb{Z}_p, k)^{\text{Ban}} \to O_k[[T]]$, which is called Amice transform. We will observe in Theorem 4.24 that $\mathcal{F}$ is an extension of Amice transform.

The $O_k$-algebra $O_k[[T]]$ forms a commutative cocommutative Hopf monoid object in $(\mathcal{E}_1^\text{ch}, \hat{\otimes}_{O_k}, O_k)$ with respect to the comultiplication $O_k[[T]] \to O_k[[T]][\otimes_{O_k} O_k[[T]]]$, $T \mapsto ((1 + T) \otimes (1 + T)) - (1 \otimes 1)$, the counit $O_k[[T]] \to O_k$, $T \mapsto 0$, and the antipode $O_k[[T]] \to O_k[[T]]$, $T \mapsto (1 + T)^{-1} - 1$. The functor $U_{1/O_k} : \text{CAlg}(O_k) \to \text{Ab}$ represented by $O_k[[T]]$ is naturally equivalent to the unitary group of dimension 1, that is, the functor which assigns to each commutative monoid object $A$ in $(\mathcal{E}_1^\text{ch}, \hat{\otimes}_{O_k}, O_k)$ the unit group $\{ f \in A^\times \mid \lim_{n \to \infty} (f - 1)^n = 0 \}$ equipped with the discrete topology. Indeed, the evaluation at $1 + T \in O_k[[T]]$ gives a natural isomorphism between them. By the definition, $U_{1/O_k}$ is an affine formal group scheme over $\text{Spf}(O_k)$. In particular, $H^0(U_{1/O_k}, \mathbb{G}_m^{1/O_k})$ is canonically isomorphic to the underlying $O_k$-algebra of $O_k[[T]]$. Therefore Amice transform can be canonically regarded as an $O_k$-algebra isomorphism $C(\mathbb{Z}_p, k)^{\text{Ban}} \to H^0(U_{1/O_k}, \mathbb{G}_m^{1/O_k})$.

The multiplicative formal group $\text{Hom}_{\text{PAb}}(\mathbb{Z}_p, \mathbb{G}_m/O_k)$ is also naturally equivalent to the unitary group of dimension 1. Indeed, the evaluation at $1 \in \mathbb{Z}_p$ gives a natural isomorphism between them. Therefore $\mathcal{F}_{\mathbb{Z}_p}$ also can be canonically regarded as an $O_k$-algebra isomorphism $C(\mathbb{Z}_p, k)^{\text{Ban}} \to H^0(U_{1/O_k}, \mathbb{G}_m^{1/O_k})$. Since Iwasawa’s isomorphism $O_k[[\mathbb{Z}_p]] \to O_k[[1 + T]]$ forms a Hopf monoid homomorphism which sends $\iota_{\mathbb{Z}_p}^*$ (1) to $1 + T$, we immediately obtain the following:

**Theorem 4.24.** The ring homomorphism $\mathcal{F}_{\mathbb{Z}_p}$ and Amice transform coincides with each other as ring homomorphisms $C(\mathbb{Z}_p, k)^{\text{Ban}} \to H^0(U_{1/O_k}, \mathbb{G}_m^{1/O_k})$.

### 5 Example

We constructed examples of Hopf monoid objects derived from groups in Proposition 3.7 and Corollary 3.8. Now we survey several examples of Hopf
monoid objects which are not derived from groups. They are helpful to grasp the computation of the dual Hopf monoid object.

5.1 General linear group Let \( n \in \mathbb{N} \). Put \( I_n := \{(i, j) \in \mathbb{N}^2 \mid i, j < n\} \). We denote by \( U_{n/O_k} \) the completion of the general linear group scheme over \( \text{Spf}(O_k) \). Then it is an affine formal group scheme over \( \text{Spf}(O_k) \) represented by the Hopf monoid object \( O_k[[T_{i,j} \mid (i, j) \in I_n]] \) with \( \mathcal{V} \)-small indeterminates in \( (\mathcal{O}_k^\text{fl}, \hat{\mathcal{O}}_k, O_k) \). The dual of the corresponding Hopf monoid object forms a cocommutative Hopf monoid object \( A_n \) in \( (\text{Ban}_{\leq}^u(k), \hat{\otimes}_k, k) \). The left regular \( A_n \)-module forms a universal family of irreducible unitary Banach \( k \)-linear representations of \( U_{n/O_k}(O_k) \) in the sense in §4.2.

When \( n = 0 \), then \( U_{n/O_k} \) is the constant presheaf associated to the trivial group, and \( A_n \) is canonically isomorphic to \( O_k[[\{1\}]] \cong O_k \). When \( n = 1 \), then \( U_{n/O_k} \) is canonically naturally equivalent to the unitary group of dimension 1, which is represented by \( O_k[[\mathbb{Z}_p]] \) by the argument in §4.3, and hence \( A_n \) is canonically isomorphic to \( C(\mathbb{Z}_p, k) \) as a Hopf monoid object in \( (\text{Ban}_{\leq}^u(k), \hat{\otimes}_k, k) \). We study an explicit presentation of \( A_n \) for the general case. Put \( \Delta_n := \{i \in \mathbb{N} \mid i < n\} \) and \( J_n := I_n \setminus \{(i, i) \mid i \in \Delta_n\} \). Since the \( O_k \)-linear homomorphism

\[
O_k^{\Delta_n \times N J_n} \rightarrow O_k[[T_{i,j} \mid (i, j) \in I_n]]
\]

\[
(c_{a,b})(a,b)_{(a,b) \in \Delta_n \times N J_n} \mapsto \sum_{(a,b) \in \Delta_n \times N J_n} c_{a,b} \left( \prod_{i \in \Delta_n} T_{i,i}^a(i) \left( \prod_{(i,j) \in J_n} T_{i,j}^b(i,j) \right) \right)
\]

is a homeomorphic isomorphism, the underlying Banach \( k \)-vector space of \( A_n \) can be canonically identified with \( C_0(\mathbb{N}^{\Delta_n} \times \mathbb{N}^{J_n}, k) \). We study its \( O_k \)-algebra structure through the presentation.

The projection \( O_k^{\mathbb{N}^{\Delta_n} \times \mathbb{N}^{J_n}} \rightarrow O_k^{\mathbb{N}^{\Delta_n}}, (c_{a,b})(a,b)_{(a,b) \in \mathbb{N}^{\Delta_n} \times \mathbb{N}^{J_n}} \mapsto (c_{(a,0)})_{a \in \mathbb{N}^{\Delta_n}} \) induces an isometric \( k \)-linear homomorphism \( C_0(\mathbb{N}^{\Delta_n}, k) \hookrightarrow A_n \). The projection corresponds to the embedding \( U_{1/O_k}^n \Rightarrow U_{n/O_k} \) into the multiplicative formal subgroup of diagonal matrices. Since \( U_{1/O_k} \) is represented by \( O_k[[\mathbb{Z}_p]] \) by Lemma 4.13 and §4.3, \( U_{1/O_k}^n \) is represented by \( O_k[[\mathbb{Z}_p^n]] \) by Remark 4.21. Therefore \( C_0(\mathbb{N}^{\Delta_n}, k) \) regarded as a closed \( k \)-subalgebra of \( A_n \) is canonically identified with \( C(\mathbb{Z}_p^n, k) \). Thus the embedding of the completion of the maximal torus corresponds to the embedding of the commutative \( O_k \)-algebra of
continuous functions on the weight space \( \mathbb{Z}_p^n \). We describe \( A_n \) in terms of difference operators on \( C(\mathbb{Z}_p^n, k) \).

For each \( i \in \Delta_n \), we denote by \( \delta_i : \Delta_n \to \mathbb{Z}_p \) the characteristic function of \( \{i\} \), and by \( \frac{\partial}{\partial \kappa_i} \) the difference operator \( C(\mathbb{Z}_p^n, k) \to C(\mathbb{Z}_p^n, k), \ f(\kappa) \mapsto f(\kappa + \delta_i) - f(\kappa) \). For an \( (i, a) \in \Delta_n \times \mathbb{N} \), we abbreviate \( \left( \frac{\partial}{\partial \kappa_i} \right)^a \) to \( \frac{\partial^a}{\partial \kappa_i^a} \). For an \( a \in \mathbb{N}^{\Delta_n} \), we abbreviate \( \prod_{i \in \Delta_n} \frac{\partial^a(i)}{\partial \kappa_i^a} \) to \( \frac{\partial^a}{\partial \kappa^a} \). For an element \( f \) of a \( \mathbb{Q} \)-algebra \( A \) and an \( a \in \mathbb{N} \), we abbreviate the binomial coefficient \( \binom{f}{a} \) to \( B_A(f, a) \).

For an \( (a, \kappa) \in (\mathbb{N}^{\Delta_n})^2 \), we abbreviate \( \prod_{i \in \Delta_n} (-1)^{a(i) - \kappa(i)} B_Q(a(i), \kappa(i)) \in \mathcal{O}_k \) to \( C(a, \kappa) \), where \( B_Q(a(i), \kappa(i)) \) is an integer and hence gives an element of \( \mathcal{O}_k \) even if \( \text{ch}(k) = p \).

By the definition, the homeomorphic \( \mathcal{O}_k \)-linear isomorphism \( \mathcal{O}_k^\mathbb{N}^{\Delta_n} \to \mathcal{O}_k[[\mathbb{Z}_p^n]] \) assigns to each \( (c_a)_{a \in \mathbb{N}^{\Delta_n}} \in \mathcal{O}_k^\mathbb{N}^{\Delta_n} \) the convergent sum

\[
\sum_{a \in \mathbb{N}^{\Delta_n}} \prod_{i \in \Delta_n} c_a(i, \delta_i) - 1)^{a(i)}.
\]

In particular, for any \( a \in \mathbb{N}^{\Delta_n} \), the delta function \( \mathbb{N}^{\Delta_n} \to \mathcal{O}_k \) centred at \( a \) corresponds to the essentially finite sum

\[
\prod_{i \in \Delta_n} (i, \delta_i) - 1)^{a(i)} = \sum_{\kappa \in \mathbb{N}^{\Delta_n}} C(a, \kappa) i_{\mathbb{Z}_p^n}(\kappa),
\]

where \( \mathbb{N}^{\Delta_n} \) is regarded as a subset of \( \mathbb{Z}_p^n \) through the natural identification \( \mathbb{Z}_p^n \cong \mathbb{Z}_p^{\Delta_n} \). Therefore every \( f \in C(\mathbb{Z}_p^n, k) \) corresponds to

\[
\left( \sum_{\kappa \in \mathbb{N}^{\Delta_n}} C(a, \kappa) f(\kappa) \right)_{a \in \mathbb{N}^{\Delta_n}} = \left( \frac{\partial^a f}{\partial \kappa^a}(0) \right)_{a \in \mathbb{N}^{\Delta_n}} \in C_0(\mathbb{N}^{\Delta_n}, k).
\]

In the case \( n = 1 \) and \( \text{ch}(k) = 0 \), the inverse correspondence \( C_0(\mathbb{N}^{\Delta_n}, k) \to C(\mathbb{Z}_p^n, k) \) is the isometric \( k \)-linear isomorphism which assigns to each \( (c_a)_{a \in \mathbb{N}} \in C_0(\mathbb{N}, k) \cong C_0(\mathbb{N}^{\Delta_n}, k) \) the continuous function \( f(\kappa) \) given as the convergent sum \( \sum_{n=0}^{\infty} c_a B_k(k, a) \) by Mahler’s theorem (cf. Theorem 1 in [3]).

For an \( i \in \Delta_n \), we denote by \( \kappa_i : \mathbb{Z}_p^n \to k \) the composite of the \( (i + 1) \)-st projection \( \mathbb{Z}_p^n \to \mathbb{Z}_p \) and the inclusion \( \mathbb{Z}_p \hookrightarrow k \). For a finite subset \( U \subset \mathbb{N}^{\Delta_n} \)
\( N^\Delta_n \times N^{J_n} \), we denote by \( E_U \in A_n \cong C_0(N^\Delta_n \times N^{J_n}, k) \) the characteristic function of \( U \). For an \((i, j) \in J_n\), we denote by \( \delta_{(i, j)} \in N^\Delta_n \times N^{J_n} \cong N^\Delta_n \sqcup J_n \) the characteristic function \( \Delta_n \sqcup J_n \rightarrow N \) of \( \{(i, j)\} \), and put \( E_{i,j} := E_{\{\delta_{(i,j)}\}} \).

For an \((i, j) \in I_n\), we define \( X_{i,j} \) as \( T_{i,j} \) in the case \((i, j) \in J_n\), and as \( 1 + T_{i,i} \) in the case \((i, j) \notin J_n\). Then the comultiplication of \( O_k[N^\Delta_n \times N^{J_n}] \cong O_k[[T_{i,j} \mid (i, j) \in I_n]] \) sends \( X_{i,j} \) to \( \sum_{h=0}^{n-1} X_{i,h} \otimes X_{h,j} \) for any \((i, j) \in I_n\).

The descriptions of the correspondence \( C(\mathbb{Z}_p^n, k) \rightarrow C_0(N^\Delta_n, k) \) and the comultiplication of \( O_k[N^\Delta_n \times N^{J_n}] \) allow us to compute the multiplication on \( A_n \) in the following explicit way:

**Proposition 5.1.** (i) For any \(( (i, j), m) \in J_n \times N\), \( E_{i,j,m}^n = m! E_{\{m \delta_{(i,j)}\}} \).

(ii) For any \(( (i, j), (j', i') ) \in J_n^2 \) satisfying \( j \neq j' \), \( E_{i,j} E_{j', i'} = E_{\{\delta_{(i,j)} + \delta_{(j', i')}\}} \).

(iii) For any \((i, j, i') \in \Delta_n^3 \) satisfying \((i, j), (j, i'), (i, i') \in J_n\), \( E_{i,j} E_{j,i'} = E_{i,i'} + E_{\{\delta_{(i,j)} + \delta_{(j,i')}\}} \).

(iv) For any \((i, j) \in J_n\), \( E_{i,j} E_{j,i} = \kappa_i + E_{\{\delta_{(i,j)} + \delta_{(j,i)}\}} \).

(v) For any \((f, b) \in C(\mathbb{Z}_p^n, k) \times N^{J_n}\),

\[
fe_{\{b\}} = \sum_{a \in N^\Delta_n} \left( \prod_{(i,j) \in \Delta_n} \left( 1 + \frac{\partial f}{\partial \kappa_i} \right)^{b_{(i,j)}} \right) \left( \frac{\partial a f}{\partial \kappa_a} \right) (0) E_{\{a+b\}},
\]

\[
es_{\{b\}} f = \sum_{a \in N^\Delta_n} \left( \prod_{(i,j) \in \Delta_n} \left( 1 + \frac{\partial f}{\partial \kappa_j} \right)^{b_{(i,j)}} \right) \left( \frac{\partial a f}{\partial \kappa_a} \right) (0) E_{\{a+b\}},
\]

where \( N^\Delta_n \) is regarded as a submonoid of \( N^\Delta_n \times N^{J_n} \) through the zero extension.

In particular, for any \((f, (i, j)) \in C(\mathbb{Z}_p^n, k) \times J_n\), we have

\[
f E_{i,j} = \sum_{a \in N^\Delta_n} \left( \frac{\partial a f}{\partial \kappa_a} (f + \frac{\partial f}{\partial \kappa_i}) \right) (0) E_{\{a+\delta_{(i,j)}\}}
\]

and \( E_{i,j} f = \sum_{a \in N^\Delta_n} \left( \frac{\partial a f}{\partial \kappa_a} (f + \frac{\partial f}{\partial \kappa_j}) \right) (0) E_{\{a+\delta_{(i,j)}\}} \) by Proposition 5.1 (v).

By the results above, we obtain explicit presentations of the commutators. For any \(( (i, j), (j', i') ) \in J_n^2 \) satisfying \( j \neq j' \) and \( i \neq i' \), we have \( E_{i,j} E_{j', i'} - E_{j', i'} E_{i,j} = 0 \). For any \((i, j, i') \in \Delta_n^3 \) satisfying \( i \neq i' \), we have
\( E_{i,j}E_{j,i'} - E_{j,i'}E_{i,j} = E_{i,i'} \). For any \((i,j) \in J_n\), we have \( E_{i,j}E_{j,i} - E_{j,i}E_{i,j} = \kappa_i - \kappa_j \). For any \((f, (i,j)) \in C(\mathbb{Z}_p^n, k) \times J_n\), we have

\[
    fE_{i,j} - E_{i,j}f = \sum_{a \in \mathbb{N}\Delta_n}(\frac{\partial^n}{\partial \kappa_i^n}(\frac{\partial f}{\partial \kappa_i} - \frac{\partial f}{\partial \kappa_j})(0))E_{a+\delta_{(i,j)}}.
\]

Suppose \(\text{ch}(k) = 0\) in the following in this subsection. We denote by \(\text{Lie}(U_n/O_k)\) the Lie algebra \(\bigoplus_{(i,j) \in I_n} k \frac{\partial}{\partial T_{i,j}}\) of \(U_n/O_k\) over \(k\), and by \(\tilde{A}_n\) the universal enveloping algebra of \(\text{Lie}(U_n/O_k)\). By the computation above, the inclusion \(\text{Lie}(U_n/O_k) \hookrightarrow A_n\) preserves the commutators, and hence extends to a \(k\)-algebra homomorphism \(\varphi_n : \tilde{A}_n \rightarrow A_n\). The following gives a description of \(A_n\) as a completion of \(\tilde{A}_n\) with respect to a seminorm:

**Theorem 5.2.** The image of \(O_k[\bigcap_{m \geq 1} \bigcap_{(i,j) \in I_n} (m, (i,j)) \in \mathbb{N} \times J_n] \subset \tilde{A}_n \), by \(\varphi_n\) is a dense \(O_k\)-subalgebra of \(A^n\).

In order to verify Theorem 5.2, we prepare several lemmata. For a \(d \in \mathbb{N}\), we put \(\mathbb{N}_d := \{b \in \mathbb{N}_n \mid (i,j) \in I_n b(i,j) < d\}\).

**Lemma 5.3.** Let \(a \in \mathbb{N}_n\). Put \(d := \sum_{(i,j) \in J_n} a(i,j)\). Then the product of \(\prod_{a(i,j)!}E_{i,j}^{a(i,j)}\) with respect to any fixed ordering on \(J_n\) is contained in \(E_{a} + \bigoplus_{b \in \mathbb{N}_d} O_k E_{b}\).

**Proof.** The assertion immediately follows from the computation of the multiplication above and the submetry of the comultiplication of \(A_n\).

**Lemma 5.4.** For any \((f, i, \epsilon) \in C(\mathbb{Z}_p^n, k) \times \Delta_n \times (0, \infty)\), there exists an \(m \in \mathbb{N}\) such that \(\|((\frac{\partial}{\partial \kappa_i})^m f)\| < \epsilon\).

**Proof.** By \(0 < |p| < 1\), it suffices to verify that for any \((f, i) \in C(\mathbb{Z}_p, k) \times \Delta_n\), there exists an \(m \in \mathbb{N}\) such that \(\|((\frac{\partial}{\partial \kappa_i})^m f)\| \leq \|pf\|\). Since \(\mathbb{Z}_p^n\) is compact and \(f\) is continuous, there is an \(m \in \mathbb{N}\) such that for any \((a_0, a_1) \in (\mathbb{Z}_p^n)^2\), \(a_0 - a_1 \leq p^m\mathbb{Z}_p^n\) implies \(|f(a_0) - f(a_1)| \leq \|pf\|\). Denote by \(\langle \bullet, \bullet \rangle\) the canonical pairing \(O_k[\mathbb{Z}_p^n] \times C(\mathbb{Z}_p^n, k) \rightarrow k\). For any \(\kappa \in \mathbb{Z}_p^n\), we have

\[
    \frac{\partial^m f}{\partial \kappa_i^m}(\kappa) = \langle (\frac{\partial}{\partial \kappa_i})^m \frac{\partial^m f}{\partial \kappa_i^m} \rangle = (f(\kappa + p^m\delta_i) - f(\kappa)) + \sum_{a=1}^{p^m-1} (-1)^{p^{m-a}} B_{Q}(p^m, a) f(\kappa + a\delta_i),
\]

and hence \(\|((\frac{\partial}{\partial \kappa_i})^m f)(\kappa)\| \leq \|pf\|\).
Lemma 5.5. For any \((f,i) \in C(\mathbb{Z}_n^p, k) \times \Delta_n\), there exists an \(\tilde{f} \in C(\mathbb{Z}_p, k)\) such that \((1 + \frac{\partial}{\partial \kappa_i}) \tilde{f} = f\) and \(\| \tilde{f} \| \leq \| f \|\).

Proof. By Lemma 5.4, \(\sum_{a=0}^{\infty} (-1)^a \frac{\partial^a f}{\partial \kappa_i^a}\) uniformly converges to an \(\tilde{f} \in C(\mathbb{Z}_n^p, k)\). By the submetry of \(\frac{\partial}{\partial \kappa_i}\), we have \((1 + \frac{\partial}{\partial \kappa_i}) \tilde{f} = f\) and \(\| \tilde{f} \| \leq \| f \|\). \(\Box\)

Lemma 5.6. The image of \(O_k[A_{\tilde{n}}(\frac{\partial}{\partial T_{i,j}}, m) \mid (m,i) \in \mathbb{N} \times \Delta_n] \subset \tilde{A}_n\) by \(\varphi_n\) is a dense \(O_k\)-subalgebra of \(C(\mathbb{Z}_n^p, O_k)\).

Proof. By Corollary 3.5 (i), it is reduced to the case \(n = 1\). By Mahler’s theorem (cf. Theorem 1 in [3]), we have \(\varphi_1(T_{1,1}) = \kappa_1\), and \(\{ B_{C(\mathbb{Z}_p,k)}(\kappa_1, a) \mid a \in \mathbb{N}\}\) generates a dense \(O_k\)-submodule of \(C(\mathbb{Z}_p, O_k)\). Therefore the assertion follows from the fact that \(\varphi_1\) is a \(k\)-algebra homomorphism. \(\Box\)

Proof of Theorem 5.2. We denote by \(A \subset A_n^\circ\) the image. It suffices to verify \(E_{(a+b)} \in A\) for any \((a,b) \in \mathbb{N}^\Delta_n \times \mathbb{N}^J_n\). Put \(d := \sum_{i \in \Delta_n} a(i) + \sum_{(i,j) \in J_n} b(i,j)\). We show \(E_{(a+b)} \in A\) by induction on \(d\). If \(d = 0\), then \(E_{(a+b)} = E_{(0)} = 1 \in A\). Suppose \(d > 0\). If \(a \neq 0\), then we have \(E_{(b)} \in A\) by the induction hypothesis, and hence \(E_{(a+b)} \in A\) by Proposition 5.1 (v), Lemma 5.5, and the bijectivity of the correspondence \(C(\mathbb{Z}_p^2, k) \rightarrow C_0(\mathbb{N}^\Delta_n, k), f \mapsto (\frac{\partial^a f}{\partial \kappa_i^a})_{a \in \mathbb{N}^\Delta_n}\). If \(a = 0\), then we have \(E_{(a+b)} = E_{(b)} \in A\) by the induction hypothesis and Lemma 5.3. \(\Box\)

By Theorem 5.2, we obtain an explicit description of universal families (cf. §4.2) of irreducible unitary Banach \(k\)-linear representations the discrete groups of \(O_k\)-valued points of closed formal subgroup schemes of \(U_n/O_k\) using completions of universal enveloping algebras.

5.2 Quantum group Continuing from §5.1, suppose \(\text{ch}(k) = 0\) throughout this subsection. We fix a \(q \in O_k\) satisfying \(|q - 1| < 1\). By Theorem 5.2, we obtain an expression of \(A_n^\circ\) as the closure of \(C(\mathbb{Z}_p^2, k)[\frac{1}{m} E_{i,j}^m \mid (m, (i,j)) \in \mathbb{N} \times J_2]\). We consider an analogous description for the \(q\)-deformation \(U_{2,q/O_k}\) of \(U_{2/O_k}\). Following the traditional formulation of the \(q\)-deformation of the commutators of the Hopf \(O_k\)-algebra \(O_k[T_{i,j} \mid (i,j) \in I_2]\) representing \(\text{GL}_2/O_k\), we define the \(q\)-deformation \(O_k[[T_{i,j} \mid (i,j) \in I_2]]_q\) of \(O_k[[T_{i,j} \mid (i,j) \in I_2]]\) as the Hopf monoid object in \((\mathcal{C}_k^{ch}, \hat{\otimes}_{O_k}, O_k)\) whose underlying Hopf monoid object is the quotient of the compact Hausdorff flat linear topological \(O_k\)-algebra freely generated by the \(\Psi\)-small set.
\{T_{q,i,j} \mid (i,j) \in I_2\} \) of non-commutative indeterminates by the two-sided closed ideal generated by

\[
\left\{ (1 + T_{q,i,i})T_{q,i',j} - q^{(-1)}T_{q,i',j}(1 + T_{q,i,i}) \big | (i, (i', j)) \in \Delta_2 \times J_2 \right\} \\
\cup \left\{ T_{q,0,0}T_{q,1,1} - T_{q,1,1}T_{q,0,0} - (q - q^{-1})T_{q,0,1}T_{q,1,0}, T_{q,0,1}T_{q,1,0} - T_{q,1,0}T_{q,0,1} \right\}
\]

and whose comultiplication is characterised by the properties that it sends

\[
1 + T_{q,i,i} \text{ to } ((1 + T_{q,i,i}) \otimes (1 + T_{q,i,i})) + (T_{q,i,j} \otimes T_{q,j,i}) \text{ and } T_{q,i,j} \text{ to } ((1 + T_{q,i,i}) \otimes T_{q,i,j}) + (T_{q,i,j} \otimes (1 + T_{q,j,j})) \text{ for any } (i,j) \in J_2.
\]

We denote its dual by \( A_{2,q} \). When \( q = 1 \), then \( A_{2,q} \) is canonically isomorphic to \( A_2 \) in \( \text{Hopf}(\text{Ban}^{\text{ur}}_{\leq}^{n}(k), \otimes, k) \), and hence \( A_{2,q} \) is a \( q \)-deformation of \( A_2 \). Since \( T_{q,0,0} \) and \( T_{q,1,1} \) commute with each other modulo the two-sided ideal generated by \( \{T_{q,1,2}, T_{q,2,1}\} \), \( A_{q,2} \) forms a \( C(\mathbb{Z}_p^2, k) \)-algebra in a way similar to \( A_2 \).

We denote by \( O_k[[T_{q,i,j} \mid (i,j) \in I_2]] \) the compact Hausdorff flat linear topological \( O_k \)-module \( \prod_{a \in \mathbb{N}^{I_2}} O_k T_{q,0,0}^{a(0,0)} T_{q,0,1}^{a(0,1)} T_{q,1,0}^{a(1,0)} \). By the definition of commutators, \( T_{q,0,0}^{a(0,0)} T_{q,0,1}^{a(0,1)} T_{q,1,0}^{a(1,0)} \), \( a \in \mathbb{N}^{I_2} \) is \( O_k \)-linearly independent, and the inclusion

\[
\bigoplus_{a \in \mathbb{N}^{I_2}} O_k T_{q,0,0}^{a(0,0)} T_{q,0,1}^{a(0,1)} T_{q,1,0}^{a(1,0)} \hookrightarrow O_k[[T_{i,j} \mid (i,j) \in I_2]]q
\]

extends to a unique isomorphism \( O_k[[T_{q,i,j} \mid (i,j) \in I_2]] \to O_k[[T_{i,j} \mid (i,j) \in I_2]]q \) in \( \mathcal{C}_k^{\text{ch}} \). Therefore it induces an isomorphism \( A_{2,q} \to C_0(\mathbb{N}^{\Delta_2} \times \mathbb{N}^{J_2}, k) \) in \( \text{Ban}^{\text{ur}}_{\leq}(k) \) in the same way as the isomorphism \( A_2 \to C_0(\mathbb{N}^{\Delta_2} \times \mathbb{N}^{J_2}, k) \).

For a finite subset \( U \subset \mathbb{N}^{\Delta_2} \times \mathbb{N}^{J_2} \), we denote by \( E_{q,U} \in A_{2,q} \cong C_0(\mathbb{N}^{\Delta_2} \times \mathbb{N}^{J_2}, k) \) the characteristic function of \( U \). For an \( (i,j) \in J_2 \), we put \( E_{q,i,j} := E_{q,\delta_{(i,j)}} \). Then we obtain the completely same results for \( A_{2,q} \) as Proposition 5.1, Lemma 5.3, and Lemma 5.6 under the careful computation of the vanishing of the contribution of \( T_{q,1,1}T_{q,0,0} - T_{q,0,0}T_{q,1,1} = (q - q^{-1})T_{q,0,1}T_{q,1,0} \). By a reasoning completely similar to Theorem 5.2, we obtain the following:

**Theorem 5.7.** The \( O_k \)-subalgebra

\[
O_k[B_{C(\mathbb{Z}_p^2, k)}(\kappa_i, m) \mid (m, i) \in \mathbb{N} \times \Delta_2] \left[ \frac{1}{m!} E_{m}^{q,i,j} \mid (m, (i,j)) \in \mathbb{N} \times J_2 \right] \subset A_{2,q}
\]

is dense in \( A_{2,q}^0 \).
We note that although $A_2$ and $A_{2,q}$ admits the same presentation of topological generators of the closed unit discs, the $O_k$-algebra structure heavily depends on $q$.

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