Flexible optoelectronics has emerged as an outstanding platform to pave the road toward vanguard technology advancements. As compared to conventional rigid substrates, a flexible technology enables mechanical deformation while maintaining stable performance. The advantages include not only the development to novel applications, but also the implementation of a wearable technology directly in contact with a curved surface. Here the monolithic integration of a perovskite-based optical waveguide amplifier together with a photodetector on a nanocellulose substrate is shown to demonstrate the feasibility of a stretchable signal manipulation and receptor system fabricated on a biodegradable material. An integrated optical amplifier–photodetector is developed in which the photocurrent is exploited that is generated in the organic–inorganic lead halide perovskite under an applied bias. Such photocurrent does not minimally perturb the amplifier operation and is used to monitor the light signal propagating along the waveguide, opening a broad range of applications for example to regulate the operation temperature.

The use of flexible materials is nowadays one of the main trends in electronics and photonics and currently shows a broad range of applications, such as deformable displays, chip to chip interconnects, mechanic tuning or sensors. Moreover, the implementation of a wearable photonic technology directly in contact with clothes would be light-weight, comfortable, noninvasive, implantable, and inherently low cost. It attracts a strong interest for industry in this futuristic field. Indeed, according to International Data Corporation, the important growth of this technology is forecasted to grow up to 213.6 millions in 2020. Nowadays, examples of commercial real-time applications include textile-based displays, photovoltaics or health monitoring. In spite of this significant progress, wearable devices still require reduced footprint, better coupling techniques, and the integration of more complex optic/electrical functionalities to meet the performances already provided by traditional semiconductors integrated on rigid substrates.

Taking into account these current limitations, metal halide perovskites (MHPs) is a promising semiconductor for flexible/wearable optoelectronic devices because of the outstanding capabilities to provide light emission, gain, generation, and photodetection functionalities of polycrystalline MHP films grown at low temperature. Indeed, MHPs demonstrated a broad range of excellent electrical and optical properties, such as long diffusion lengths, high absorption cross-section, high quantum yield of emission at room temperature, or tunable bandgap with the composition. MHP-based devices include highly efficient solar cells, optical active devices, and photodetectors. The majority of these publications, however, use a rigid substrate to fabricate the device, being a significantly lower amount of works on MHP flexible devices with a single functionality as solar cells, optical switch or lasing. On the other hand, nanocellulose (NC) has been probed as an ideal substrate for wearable optoelectronics. This polymer is obtained from the most common biopolymer on Earth, and it consists of rigid nanocrystals that can be easily assembled into films and gel materials. NC is not only an excellent bendable, deformable and stretchable material, but also exhibits very interesting properties for optoelectronics. Its advantages comprise a very high transparency in the visible range, tunable chiral nematic order by the surface chemistry, low roughness, and extremely high gas barrier properties. Nevertheless, despite these promising abilities, integration of optoelectronic devices in cellulose has been elusive, being it polyimide or polydimethylsiloxane.

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the most common flexible substrates. To the best of our knowledge, there are very few reports of its use in combination with MHP for the preparation of solar cells; with very limited performance but exhibiting a good potential for encapsulation.

In the present work, we propose a step forward in the design of wearable optoelectronic devices by the development of an integrated optical amplifier–photodetector on a biocompatible/biodegradable NC substrate, based on polymer/MHP waveguides (WGs). Our approach to integrate MHP-based optoelectronics/photonics on flexible NC demonstrates: (i) an easy fabrication method to integrate the perovskite and electrodes onto a flexible and biocompatible NC substrates, (ii) a suitable design of the WG structure to enhance the optical gain of the MHP and the generated photocurrent, (iii) the successful integration of the photonic (WG-amplifier) and the optoelectronic (photodetector) components within the same flexible device, and (iv) an in situ monitoring of the photoluminescence signal inside the optical WG-amplifier through the generated carrier photocurrent. This configuration opens a broad range of electronic applications, we stress this point in the present work showing how the system could be an element of the electronic circuitry to regulate the operation depending on temperature.

The integrated WG amplifier–photodetector proposed in this work allows simultaneously the amplification of emitted light by the MHP and the signal monitoring by the photocurrent detected at metal contacts separated by the WG, as illustrated in Figure 1a. Essentially, we exploited the optical confinement at the WG, due to the refractive index contrast between the MHP core (2.24 at 780 nm) with very limited performance but exhibiting a good potential for encapsulation.

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Figure 1d). Since this compact device is implemented in a flexible NC substrate, it allows bending and wearable properties (see Figure 1e).

Mode analysis carried out on a PMMA/MHP bilayer structure of 0.85/0.35 μm reveals that the pump beam at 532 nm supports the first three propagation modes in each polarization (see Section S12 in the Supporting Information). These modes are spatially distributed along the semiconductor (TE₀ and TE₁) and the polymer (TE₂) with negligible difference between the transverse electric (TE) and magnetic (TM) polarizations, thus the discussion about TE can be extended to TM modes. Propagation at 532 nm along the TE₀ and TE₁ modes, however, is inhibited by the high absorption coefficient of the MHP at this wavelength (about 13 μm⁻¹).[11,12] and hence pump beam at 532 nm mainly travels along the TE₂ mode (see Figure 1f) whose losses are reduced down to 0.05 μm⁻¹. In these conditions, evanescent field of TE₂ in the MHP (0.3% overlap) generate PL at 780 nm along the entire length (~1 mm) of the WG. On the opposite, the TE₀ and TE₁ modes supporting the propagation of PL peaked at 780 nm are highly confined (70% overlap) in the MHP, see Figure 1e, and will promote amplification of the spontaneous emission (ASE) for high enough laser excitation fluencies. Indeed, we already demonstrated that the PMMA layer on top of MHP (in this case deposited on a rigid substrate) produced a double beneficial effect that assured low ASE threshold:[15] (i) PMMA encapsulates the perovskite making the device stable over several months,[16] and (ii) The low losses of the mode at 532 nm confined in the PMMA allows a nearly uniform excitation of the MHP layer in the WG structure. For comparison purposes a less demanding rigid system PMMA/MHP integrated in silicon substrates has been also produced and characterized. In this configuration, a pump fluency of about 100 nJ cm⁻² corresponds to ≈2 × 10¹⁰ photons cm⁻², which gives rise to ≈3.5 × 10¹⁸ electrons per pulse cm³ from valence to conduction band (~E: α/hν, where E is the pump fluency, α the absorption coefficient and hν the energy of the incident photon). Assuming the aforementioned uniform excitation and the geometrical parameters of the excited MHP film (100 μm wide, 0.5 μm thick, 1 mm length) 1.7 × 10¹¹ electron–hole pairs/pulse will be generated in the whole waveguide at the ASE threshold. Since the passivation of grain boundaries in MHP film,[16,34] lead to an enhancement of the emission quantum yield up to 70%.[35,36] most of these pairs potentially will recombine radiatively increasing the PL signal.

Simultaneously, the application of an electric field when the MHP is optically pumped will promote a portion of those photogenerated carriers toward the external electrical circuit, i.e., give rise to an electrical photocurrent (transversal cross section in Figure 1g). The photosresponse of the photoco nductive detector under illumination is analyzed simultaneously with the PL/amplification experiment for different applied bias, where the electric field can be also tuned by using different gap distance between electrodes (see Figure 1f). As a result, the device demonstrates photocurrents of 10–100 nA (varying slightly for different fabricated devices and electrode gap distance) under low bias voltages (5–10 V) at the ASE threshold energy inside the WG, which is observed at ~4 nJ with a line width of ~5 nm. Indeed, we demonstrate very close performance of the sub-system fabricated on NC standing over both rigid and flexible holders/supports. Therefore, our approach paves the road of a future technology for wearable devices that could be directly printed on paper or incorporated in clothes or other curved surfaces by using NC as intermediate substrate.

MHP films deposited on NC were firstly examined under surface illumination in order to establish their optical and electro-optical properties as compared to the same films deposited on rigid substrates. The absorption coefficient of the films as a function of wavelength (left axis of Figure 2a) presents a sharp band edge beginning at around 770 nm (1.61 eV), a visible exciton resonance at 750 nm (1.65 eV) and a monotonous increase below the bandgap wavelength, in agreement with previous publications.[11,12] Indeed, the NC substrate did not introduce any significant spectral changes as compared to the film deposited on glass (see Figure 2a). Similarly, PL under low fluencies shows similar spectrum for both films deposited either on glass or on NC (see Figure 2a). In both cases the MHP film exhibits ASE for high enough excitation fluencies (1 ns pulsed laser at 532 nm with 1 KHs of repetition rate) (see Figure 2b).[12,13] The Gaussian-shaped PL band centered at ~780 nm with a full width at half maximum (FWHM) ≈55 nm becomes an intense and narrow Lorentzian ASE line with FWHM <10 nm (Figure 2b) centered at 785 nm. The slight redshift in the ASE peak as compared to the maximum of PL is usually found in ASE devices,[11,12] which is due to the reabsorption effect of photons produced at the high energy tail of the PL.

It is important to highlight that ASE threshold, ~10 μJ cm⁻² shown in Figure 2b, is very similar in MHP films deposited on both glass and NC substrates, as observed in the inset of Figure 2b; this value is in agreement with other studies.[37] This result confirms the good optical quality deduced from absorption/PL measurements in both cases. The observed slight increase of the ASE threshold in NC samples can be initially attributed to a higher contribution of nonradiative channels, which can be related to the smaller grain size of MHP on NC measured by atomic force microscope (AFM). According to the kinetics study shown in Figure 2c, the experimental decay time of the PL measured on these MHP films under low excitation fluencies (below ASE threshold) is slower when deposited in glass than in NC substrates. Indeed, the data were fitted by an effective decay time, τ_eff, of 13 and 6 ns for glass and NC, respectively. The excitation radiative lifetime in our MHP films results to be τ = 18.6 ns, as estimated from the relation 1/τ_eff = 1/τ_r + 1/τ_nr, where τ_r is the nonradiative recombination time, and the quantum yield (QY = τ_eff/(τ_r + τ) of ~70% for MHP films reported elsewhere.[36,37] By taking into account that τ should be the same in both substrates, the nonradiative recombination time for MHP deposited on NC is τ_nr(NC) = 8.9 ns (whereas τ_nr(glass) = 43 ns), which would give a drop in the QY up to 32%. It is difficult to give a precise microscopic origin of the increased influence of nonradiative channels (smaller nonradiative times in perovskite on nanocellulose as compared to that on silicon/SiO₂), but possibly is related to an increased density of point/linear crystalline defects in the case of nanocellulose promoted by its surface peculiarities and subsequent perovskite crystallization as compared to SiO₂.

In addition, the lower thermal conductivity of NC (0.22–0.53 Wm⁻¹ K⁻¹)[39] as compared to glass (~1 Wm⁻¹ K⁻¹) can also influence the ASE threshold difference. Indeed, the ASE
spectra registered in the case of MHP on NC (Figure 2b)
where unstable after some minutes, as compared to the films
deposited on glass that demonstrated good stability under the
same laser excitation conditions. On the opposite, a stable
ASE operation in MHP was observed when the repetition rate
was reduced down to 100 Hz, probably because a duty cycle of
10 ms between ns-pulses allows a sufficient cooling recovery
(see Section SI3, Supporting Information).

Several sample series were processed under ambient con-
ditions to measure wave-guided PL signal and photocurrent
to check for reproducibility. Both dark current and photocur-
rent were measured through the deposited two metal contacts
defining the photoconductor, and they yield different values of
resistivity and responsivity from sample to sample, as indicated
in Table 1. From I–V curves under dark conditions (see Sec-
ton SI4, Supporting Information), the resistivity measured in
most of the films are within the range $3 \times 10^3–3.5 \times 10^5 \ \Omega \ \text{cm}$,
being found the larger dispersion in the case of the thinnest
samples, likely due to the greater thickness inhomogeneity
and surface roughness (in the case of NC). The smallest values,
$\approx 3–5 \times 10^4 \ \Omega \ \text{cm}$, are measured in 500 nm thick films depos-
ited on NC, similar to values previously reported.$^{[40,41]}$ In other
samples, where the MHP was deposited either on NC or SiO$_2$/
 silicon, the resistivities were as high as $10^5 \ \Omega \ \text{cm}$. In these
cases, assuming a mobility of $\approx 10 \ \text{cm}^2 \ \text{V}^{-1} \ \text{s}^{-1}$ as proposed
elsewhere.$^{[42]}$ the electron concentration would be as low as
$10^{13} \ \text{cm}^{-3}$, which can be related to a near intrinsic semicon-
ductor behavior.$^{[43]}$ In samples exhibiting this more intrinsic
behavior the dark current will be smaller, hence being more
sensitive to low light levels for which higher responsivity
would be possible to measure.$^{[44]}$ In this way, a certain min-
imum concentration of photogenerated carriers are needed to
overcome the background electron concentration in thermal

| Table 1. Electrical and electro-optical properties of MHP films (350 and 500 nm thick) prepared under ambient conditions on NC and SiO$_2$/Si substrates. Responsivity measured through electrodes separated 0.1 and 1 mm are compared at bias voltages 2 and 20 V given its linear depend-
ence with electric field. |
|-----------------------------|-----------------------------|
|                           | MHP on nanocellulose | MHP on SiO$_2$/Si |
|-----------------------------|-----------------------------|
| Resistivity [10$^4$ $\Omega$ cm] | 1.2–12 | 0.3–1.9 | 2–35 | 5–20 |
| Responsivity g = 0.1 mm (2 V) [mA W$^{-1}$] | 0.067 | 0.072 | 1.730 | 0.110 |
|                          | g = 1 mm (20 V) [mA W$^{-1}$] | 0.020 | 0.085 | 0.640 | 0.390 |

Figure 2. Light absorption, photoluminescence and photocurrent characterization of films and integrated devices. a) Absorption (symbols and left axis) and PL intensity (solid lines and right axis) of a 350 nm thick MHP layers spin coated on glass (green) and NC (orange) (held on glass). b) PL spectra of MHP deposited on NC measured under back-scattering geometry (laser focused on the surface of the samples) for different excitation fluencies; above a threshold of $\approx 15 \ \mu$J cm$^{-2}$ the PL spectra narrows and its intensity grows superlinearly, clear signatures of stimulated emission; the inset compares the PL intensity as a function of the excitation fluency for MHP deposited on NC (orange symbols) and MHP deposited on glass (green symbols). Note the logarithmic scale on Y-axis. c) Time resolved photoluminescence spectra of the MHP layer deposited on glass (green) and NC (orange) measured under a low excitation fluency of 30 nJ cm$^{-2}$; symbols and solid lines refer to experimental data and fitting, respectively; gray shaded area corresponds to the system response. d) Photocurrent as a function of the applied voltage (inset corresponds to the experimental setup) under a CW excitation at 532 nm in a 350 nm thick MHP layer spin coated on a SiO$_2$/Si substrate (green symbols) and on NC (orange symbols) in a photoconductor device with a gap distance between electrodes $g = 0.1$ mm.
equilibrium in order to give an appreciable photocurrent density $J_{\text{phot}} = J_{\text{dark}} + J_{\text{ph}} = e\mu_i n_0 + e\mu_p \Delta n$, assuming a n-type character for the MHP,\cite{17,18} consistently with better responsivity values measured in more resistive films (Table 1).

In MHP films under low illumination level (60 mW cm$^{-2}$ at 532 nm under normal incidence, see inset in Figure 2d) exhibit a noticeable photocurrent of $2 \times 10^{3}$ and $10^{4}$ nA (at 15 V of bias voltage, i.e., low applied electric field =1.5 kV cm$^{-1}$) in SiO$_2$/Si and NC substrates, respectively, as observed Figure 2d. The lower photocurrent of the films deposited on NC is again attributed to nonradiative carrier losses, but also to the smaller resistivity (higher dark current in this NC sample) and the worse thermal conductivity of NC.

The temporal response of the device seems to be limited by the RC constant of the photodiode conductor circuit ($R = 1$ MΩ, $C = 330$ pF), because it is observed a frequency bandwidth below 1 kHz, and the RC constant of the photodiode itself that gives a time constant of around 20 µs due to the high resistivity of the MHP film, see Figure S18 (Supporting Information), at least for the excitation laser used in the experiments with 20 kHz of repetition rate. In any case, this is not a limitation factor for the concept device demonstrated in this work and future improvements are possible by optimizing both factors (photodiode and its external circuit).

The MHP amplifying device fabricated on NC was studied under end-fire coupling of a pulsed laser pumping at 532 nm (WG geometry, as shown in Figure 3a). Here it is worth to note that we have tested the amplifier device on NC supported on glass (Figure 3a) or directly the stand-alone NC (see Section S16, Supporting Information) with similar results. In both cases, the ASE signal collected from the output edge of the WG as a guided mode (see Figure 3b) exhibits a narrow peak (whose linewidth is 5 nm for the highest laser excitation power used in the experiment, as indicated in Figure 3c) that grows superlinearly above a threshold of $\approx 4$ nJ, as observed in Figure 3d. This behavior is quite similar as the one observed above under backscattering geometry and previously reported in similar structures integrated on a Si/SiO$_2$ rigid substrate.\cite{15}

Such a superlinear growth of the PL intensity (see Figure 3d) would follow a potential increase $I_{\text{PL}} \propto I_{\text{PUMP}}^{2.5}$, which would correspond to a gain $G = 10 \text{ dB cm}^{-1}$ at the output edge of the waveguide ($L = 1$ mm long)\cite{15} or, in other words, a modal gain ($g = \frac{G}{L} = 23 \text{ cm}^{-1}$) close to the material gain ($g = \Gamma \cdot g_m$) since the confinement factor of the optical modes in the MHP film is close to 1. Here it is worth mentioning that PL intensity was stable during the measurement, although similar excitation conditions (20 kHz excitation source) did not show a stable ASE production under backscattering geometry. Therefore, the high confinement of emitted light by the active medium provided by this WG structure enhances the generation of light, and triggers the ASE regime. Moreover, the excitation fluencies shown in Figure 3c,d correspond to excitation light coupled with the whole PMMA/MHP/NC structure with a cross section of about $2 \times 10^{-3}$ cm$^2$. Nevertheless, since this device propagates the light along the PMMA layer, only a 0.3% of the TE$_2$ mode at 532 nm travels along the MHP, reducing the thermal heating of the semiconductor and the effective ASE threshold ($E_{\text{th}}$) down to 600 nJ cm$^{-2}$, one order of magnitude smaller than that measured under backscattering geometry in Figure 2b. This $E_{\text{th}}$ corresponds to an average power of the external pumping laser as low as 0.8 mW, which is estimated by taking into account a coupling efficiency =10% inside the waveguide and the repetition rate (20 KHz) of the pulsed laser.

Under the above given excitation conditions, the photocurrent mainly monitors photogenerated carriers by the pump beam travelling along the 1 mm long PMMA/MHP WG, the same distance covered by the Au electrodes. The photocurrent, $I_{\text{PC}}$, variation presented in Figure 3d indicates a clear correlation between $I_{\text{PL}}$ and $I_{\text{PC}}$, where $I_{\text{PC}} \propto I_{\text{PUMP}}^{1/2}$ before the saturation observed above $E_{\text{th}}$. Moreover, $I_{\text{PC}}$ and $I_{\text{PL}}$ dependences can be nicely fitted (solid lines in Figure 3d) with the model developed in Section S17 (Supporting Information). The simulations reveal a transparency carrier concentration for stimulated emission $N_0 = 1.5 \times 10^{18}$ in agreement with previous results.\cite{16} This square root law for $I_{\text{PC}}$ as a function of the excitation fluency corresponds to the high carrier injection regime, while its saturation is attributed to the gain saturation mechanism in optical amplifiers,\cite{24} where the increment of photogenerated carriers over $N_0$ is transformed into photons (stimulated

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**Figure 3.** Characterization and modeling of the flexible device. a) Picture of holder and photodevice with end-fire excitation/collection objectives. b) PL decoupled at the output edge of the waveguide. c) PL intensity measured for different excitation fluences collapses to a narrow peak of about 10 nm above a certain threshold. Note the logarithmic scale on Y-axis. d) PL intensity (blue symbols) as a function of the excitation fluence demonstrates a superlinear growth of the PL above the 4 nJ threshold, while photocurrent shows a sublinear increase (red symbols) before saturation, in agreement with the model (solid lines), as explained in the text; photocurrent was measured by applying 10 V on gold electrodes with $g = 1$ mm.
emission regime). In this way, the highest excitation fluencies reveal $I_{PC}$ up to 25–50 mA cm$^{-2}$ for 100–600 V cm$^{-1}$ applied electric fields inside the waveguide. Finally, it is worth mentioning that the device-on-NC presents again features very close to those obtained for MHP films on rigid substrates (see Section S18, Supporting Information), except by a slightly higher peak energy threshold (4 instead of 2 nJ) and ASE linewidth (5 nm instead 2–3 nm) and higher photocurrents.

The integrated amplifier–photodetector device can be used for many applications related to signal amplification and processing at 780–790 nm (telecom, sensing, and other fields) but also at shorter/longer wavelengths by changing the metal or the halide in the MHP compound. One example is highlighted in Figure 4. A primary use would be the control itself of the optical amplifier to fix the threshold of operation, specially under temperature changes. If laser flux is fixed below the threshold the PL peak intensity decreases above room temperature (spectra in Figure 4a and blue solid circles in Figure 4c), whereas the photocurrent measured simultaneously at the photodetector suffers a slight monotonous increase (blue hollow circles in Figure 4c), as expected if the population of free carriers increases with temperature as compared to that of free excitons. However, if laser flux is fixed just above the threshold, the PL peak at the ASE wavelength decreases in a similar way (spectra in Figure 4b and red solid squares in Figure 4c), but this time the photocurrent is practically constant up to room temperature (red hollow squares in Figure 4c), due to its saturation regime (see above), and increases much faster when increasing temperature because the ASE regime is progressively lost against spontaneous emission.

In this work, we propose the monolithic integration of a WG amplifier–photodetector system in a flexible nanocellulose substrate for future wearable applications. The device allows an in situ monitoring of PL signal (in spontaneous and ASE regimes) decoupled at the edge of the waveguide by studying the photocurrent generated by the pump beam generating this PL. For this purpose, we successfully integrated a PMMA/ MAPbI$_3$ bilayer structure on the cellulose substrate without any significant degradation of the semiconductor, and inject the excitation light at the input edge of the flexible substrate. As a result, ASE is demonstrated with similar performances as those reported for rigid substrates. Moreover, we demonstrate the simultaneous photodetection of light photogenerating carriers in the MHP film by means of the integrated photoconductor with the WG amplifier. The resulting photocurrent demonstrates a clear correlation with the intensity of PL under spontaneous and ASE generation regimes as a function of the laser excitation fluency. Moreover, the different behaviors of the photocurrent in the two regimes will allow a broad range of applications, such as trigger generation, gain automatic control, signal processing for visible telecommunications and sensing. This potentiality has been demonstrated by varying temperature below and above room temperature. Therefore, the present work paves the road for the future integration of wearable photonic components using cellulose substrates.

### Experimental Section

**Products and Substrate Preparation:** All chemicals were used as received. N,N-dimethylformamide (DMF) anhydrous, 99.8%, dimethyl sulfoxide (DMSO) anhydrous ≥99.9%, toluene anhydrous, 99.8%, and poly(methyl methacrylate) (PMMA) with average molecular weight of 350 000 were purchased from Sigma-Aldrich, methylammonium iodide (MAI) was purchased from DYESOL, and PbI$_2$ 99.99%, was purchased from TCI. MHP solutions with concentrations of 1.35 and 2.025 m were prepared by adding 1 mL of DMF and 95 μL of DMSO into each vial containing 622 and 933 mg of PbI$_2$. The solutions were heated at 65 °C to dissolve PbI$_2$. After cooled down to the room temperature, they were poured into corresponding vials containing 215 and 322.5 mg of MAI to make final solutions. PMMA solutions with concentrations of 99, 110 and 140 mg mL$^{-1}$ in Toluene were prepared by stirring.

**Device Fabrication:** Cellulose nanocrystals were obtained via TEMPO-mediated oxidation procedure slightly. The initial aqueous solution was composed by 10 g of Kraft pulp immersed in 1 L of purified water and stirred with a magnetic stirrer for half an hour. Later, the solution was sonicated for other 30 min in a 350 Watt ultrasonic bath, obtaining a preliminary homogeneous suspension of cellulose. Oxidant and catalyst species (0.162 g of TEMPO, 1,000 g of NaBr and 35 mL of NaClO) were added to the solution under stirring. The pH was monitored during the reaction and maintained at a value between 10.5 and 11 through the addition of 1 mL of 1 M NaOH at time. Once stabilized, the pH was neutralized by diluting the solution and letting the cellulose to deposit on the bottom of the bicker and then washed with purified water: the washing was repeated 15 times with at least 400 mL of water each. Cellulose concentration was measured weighing a known quantity of solution, subsequently placed in an oven at 60 °C. Once completely dried, the remaining cellulose was weighted again. Typical values were in the range 3–5 mg mL$^{-1}$. The concentration can be tuned by either dilution or concentration through water evaporation. The mechanical disintegration to release the nanofibers was achieved through sonication using a Bandelin Sonopuls HD 2200 ultrasonic homogenizer with a 13 mm diameter ultrasonic tip for 2 min at 20 kHz frequency and 100 W output power. This step was repeated twice for every sample, obtaining transparent NC fibrils suspension. Finally, the films were obtained by
pouring the clear suspension on a 8.5 cm diameter Petri dish and drying it at 60 °C in an oven. The oven was equipped with a flat copper foil to maintain homogeneous temperature over the whole layer surface. The solution dried for 36 h, at the end a transparent and homogeneous film could be peeled off. These were stored at room temperature in a dehumidified container. To be handled NC films need to have 10–20 µm of thickness. This can be obtained by varying either the amounts of the poured solution or by changing the NC concentration. Samples used for the perovskite deposition were 20 µm thick (see Supporting Information section for more details). Then, NC was attached to glass substrates by using double sided tape at margins. In order to have a uniform and homogeneous layer of perovskite on plain glass and NC, substrates were ozone treated for 15 min just before spin coating of perovskite. MHP films were deposited by spin-coating of 50 µL of 1.35 and 2.025 µsolutions for 50 s at 4000 and 3000 rpm, respectively. During spin coating, anti-solvent method was employed in order to help in the film crystallization, washing with nonpolar diethyl ether just before formation of white crystals in the substrate. At 30 and 60% RH, this could be relatively 8–9 and 12–13 s after starting the spin coating. Then substrates were annealed at 100 °C for 3 min. At the end of the process 350–500 µm thick MAPbI3 films (thickness is controlled with the spin coating speed) were deposited on the NC. Once the perovskite was properly deposited on the flexible substrate, 1 mm² square and 30 nm thick Au electrodes were evaporated on the semiconductor. Then, gaps of 100, 500, and 1 µm were patterned by protecting the sample with an aluminum mask. Finally a ~1 µm thick PMMA film is spin coated for 3000 rpm on the perovskite as capping layer and post baked at 80 and 150 °C each temperature. Here evaporated gold electrodes defining the photodetector were deposited with a resist before PMMA deposition, in order to enable the final bonding of silver wires with silver paint. The biocompatibility and flexibility of the cellulose substrate allows the device-on-cellulose to be easily worn on or incorporated to any kind of substrate or surfaces. Here it was deposited on a polyimide strip (one side glued) to allow an easier examination of the electrical properties. For this purpose, edges of the sample were carefully cut with a thin blade from the back side (polymer strip). For electrical measurements, the whole device-on-cellulose/polymer stripe structure was pasted on glass in order to allow an easier bonding of Au wires and the electrical connections.

Structural Characterization: The morphology of the films was analyzed by SEM using a JSM7000F (field emission scanning electron microscope). The XRD patterns of the samples were measured using a X-ray diffractometer (D8 Advance, Bruker-AXS) (Cu Kα, wavelength λ = 1.5406 Å).

Optical Characterization: The device was examined at room temperature and ambient conditions by end-fire coupling a Nd:Yag laser doubled at 532 nm (SN-P20F-100 supplied by Team Photonics, France) at the input edge of the sample (pulse of 1 ns 20 KHertz repetition rate) with the aid of a 40x microscope objective (see Figure 1a). The waveguide PL of the MAPbI3 at 780 nm (Figure 1a) was collected at the output edge of the structure with a 20x microscope objective and focused into a fiber optic connected to a HR4000 Ocean Optics spectrometer (estimated overall resolution better than 0.7 nm). Time resolved PL was carried out by focusing the PL into a Hamamatsu C5658-3769 avalanche photodetector connected to a BOXCARDCPS-150 electronics from Becker & Hickl GmbH. Photocurrent (see Figure 1a) is analyzed by applying an electric field between the Au electrodes and measuring the generated current by using a Keithley’s Series 2400 Source Meter Unit (SMU). Detection below 1nA is limited in some cases by the dark current of the photodetector and resolution of the multimeter. Frequency dependence experiments were carried out by illuminating the samples under continuous wave (CW) excitation at 532 nm (Z40M18B-Z, Laser Optoelektronik GmbH, Germany) chopped at a controlled frequency. Then photocurrent generated by the application of the external voltage with the SMU is synchronously detected with a lock-in amplifier (SR810, Standford Research Systems) by previous filtering the DC component with a RC circuit. Time dependence electrical experiments were performed by detecting the photocurrent with the scope GDS-8208 (GW Instek, Taiwan). Additional characterization was performed by focusing the excitation beam on the top of the sample and measuring the back-scattering PL/photocurrent with the same set-up. In addition, samples were also examined under CW excitation at 532 nm, and 1 ns pulsed Nd:Yag laser doubled at 532 nm with variable repetition rate 100–1 KHz (FTS355-Q4-1KHZ adapted at 532 nm and supplied by CryLas Laser Systems, Germany). Temperature measurements were done by using a Peltier device with area 1 cm².

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Keywords
flexible devices, nanocellulose, optical amplifiers, perovskites, photodetectors

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