Microwave Photonic MIMO Radar for Short-Range 3D Imaging

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ABSTRACT In the fields of radar imaging and detection, the use of optical components appears as an attractive solution to overcome limitations of current technologies. This paper focuses on the development of a new class of microwave-photonic radar imaging systems enabling volumetric image reconstruction. These operations are made possible using a multiple-input multiple-output antenna array architecture combined with the conception of a dedicated optical multiplexing technology to limit the complexity of the whole reception chain. Particular emphasis is placed on the development of mathematical formalisms specifically adapted to these microwave-photonic radar architectures, making it possible to model the measurements carried out and to reconstruct three-dimensional radar images. These solutions are validated by the reconstruction of complex scenes with a multiple-input multiple-output radar made of up to 16 transmitters and 16 receivers.

INDEX TERMS MIMO radar, ultra-wideband radar, microwave imaging, microwave-photonic components, electro-optical conversion.

I. INTRODUCTION

In the recent years, solutions based on the use of photonic components have been increasingly investigated to overcome the limits induced by radio frequency (RF) components in the framework of satellite communication [1], wireless access networks [2] or radar detection [3].

The growing maturity and availability of electrical-to-optical conversion technique makes possible to take advantage of the many properties of optical systems such as low propagation losses, immunity to electromagnetic interference and large bandwidth. In the field of radar detection, these components are then used in RF systems to generate highly coherent RF signals [4]–[6] or to allow RF information to be transmitted over long distances [7]–[9]. They are also integrated to perform high speed beam-forming operations [10]–[14], or to reduce the constraints associated with the use of high-frequency signals, in particular by means of the photonic de-chirp technique [15]–[21]. These hybrid architectures, at the frontier between optics and microwaves, offer greater flexibility than pure RF systems by taking advantage of the interesting guidance and immunity properties of optical components.

In this paper, the optical components are implemented in the reception part of a short-range imaging system to permit ultra-fast acquisition of multiplexed signals reflected from a region of interest. This system, initially intended for threat detection in public places, needs to provide large spatial diversity and fast acquisition for real-time scanning operations [22]–[24]. To this end, the use of a Multiple-Input Multiple-Output (MIMO) array makes possible the formation of large synthetic apertures with a limited number of radiating elements. Nevertheless, this architecture requires individual antenna control in order to measure all the interactions between transmitters (Tx) and receivers (Rx) used for image reconstruction. MIMO systems based on photonic components have already been proposed but the developed systems needed a number of acquisition channels equal to the number of receiving antennas [25], [26]. To reduce the complexity of the receiving architecture, it is therefore interesting to measure all the reflected signals on a single channel. There are already a variety of solutions based entirely on
the use of RF components that address these concerns. One of these solutions consists by using an RF switching matrix [27]. Nowadays it is possible to find off-the-shelf solutions achieving switching times or less than 100 ns. However, conventional solutions are mostly limited by their number of channels and require special attention to optimize their synchronization, allowing signals to be acquired as quickly as possible. Another solution to measure all the receiving signals is proposed in [28], [29]. In these papers the authors used chaotic cavities to code and multiplex the signals reflected by the scene, but were limited by a significant level of transmission loss and a difficult characterization of radiated fields.

The prototype developed here makes possible to acquire in one shot all the reflected signals on a single acquisition channel with a space-saving architecture. For this purpose, it is composed, among other things, of an RF switching matrix for transmission and an optical time-division multiplexing system for reception. A basic proof of concept was initially proposed with a 1 × 4 single-input multiple-output far field radar [30] and latterly extended to the design of a 16 × 16 MIMO setup [31]. As a continuation of these efforts, this paper first proposes a complete and rigorous description of the whole system by introducing for the first time a complete analytical formalism that permits to model the overall operation of this type of opto-microwave radars. These developments then make it possible to propose algebraic reconstruction techniques for the estimation of volumetric images, highlighting in particular a possible model reduction in order to accelerate this process. In addition, an advanced description of the optical multiplexing process is provided, focusing on the operation of the microwave photonic summation device developed by Xlim research institute and specifically improved for these activities. Experimental validations of volumetric reconstructions are detailed, putting into practice the techniques proposed for the imaging of complex scenes.

Analytical formalisms and reconstruction techniques are exposed in the first part of this paper. The explanation of the implementation of the time-division multiplexing system with optical components follows in a second part. The third part focuses on the presentation of the 16 × 16 MIMO prototype operating in the 5.5-7.5 GHz band. Finally, the last part presents the calibration method and the results obtained in order to show the performances of the full system. A conclusion is proposed at the very end to give an overview of the document.

II. MATHEMATICAL MODELING OF A MIMO SYSTEM WITH TIME MULTIPLYING STRUCTURE AT RECEPTION

The overall architecture of a MIMO system consisting of nTx transmit and nRx receive antennas is presented in Fig. 1. The developed model considers four approximations:

- Isotropic and single polarized antennas are used to simplify the interaction with the target to a scalar model.
- The transmitted signal is normalized and therefore does not appear in the equations.
- RF components are considered ideals. Therefore, only the time division multiplexing system has non-zero delay groups.
- Multiple scattering is ignored in the context of Born’s first approximation.

Following these conditions, the signals measured by the receive antennas can be defined, in the frequency domain and at each frequency, as:

$$S_f(r_t, r_r) = S_f^{coupling}(r_t, r_r) + \int E_f^T(r_t, r) \sigma(r) E_f^R(r_r, r) d^3r$$

These signals are accounting for the interactions between transmitted and received electric fields with the target, noted respectively $E_f^T$ and $E_f^R$. These are radiated by the antennas of respective locations $r_t$ and $r_r$ in the region of interest $r$.

The interaction with the target is defined by the scalar electric susceptibility model noted $\sigma$, also commonly referred as the reflectivity function of the target. Finally, $S_f^{coupling}(r_t, r_r)$ is the direct coupling between each transceiver pair. The radiation of an antenna, whether transmitting or receiving, can be defined as a function of its position $r_a$ as follows:

$$E_f(r_a, r) = \int J_f(r' - r_a) G_f(r', r) d^3r'$$

where $J_f$ corresponds to a volume current density radiating in the region of interest according to the Green’s functions, defined in free space as:

$$G_f(r', r) = \frac{\exp(-j\frac{2\pi|f|}{c}|r' - r|)}{4\pi|r' - r|}$$

Generally, Eq. (1) is the starting point for image reconstruction. In the proposed approach, the received signals are time multiplexed by a microwave-photonic system in order to limit the number of receiver chains. The expression of the measured signals $U_f(r_t)$ is as follow:

$$U_f(r_t) = \sum_{r_r} C_f(r_r) S_f(r_t, r_r)$$
where $C_f(r_f)$ corresponds to the pre-characterized transfer functions of the time multiplexer.

Stemming from the Eq. (4) two methods can be proposed to retrieve the image of the scene. In order to simplify the reading of the following equations the direct coupling term is not considered, which corresponds, from a practical point of view, to the implementation of a time-gating on the reflecting signals. Moreover, the used antennas are considered as isotropic. In this case the Green’s function are enough to describe the propagation terms.

1) METHOD 1: INVERSION OF THE FULL MODEL
The first technique consists in building a full operator taking into account the terms of propagation in space and the transfer function of the time multiplexer. For that $C_f(r_f)$ must be integrated in the integral function:

$$U_f(r_i) = \int_r \sigma(r) G_f(r, r) \sum_{r_f} C_f(r_f) G_f(r, r_f) d^3r$$ (5)

A single operator can then be defined to map the measured signals to the space to be imaged:

$$H_f(r_i, r) = G_f(r, r) \sum_{r_f} C_f(r_f) G_f(r, r_f)$$ (6)

Through this substitution, this formalism can finally be expressed as a Fredholm integral equation:

$$U_f(r_i) = \int_r H_f(r_i, r) \sigma(r) d^3r$$ (7)

The problem is finally discretized and written in a matrix form by vectorizing all the measurements and unknowns. Bold font is thus used to denote the vector and tensor quantities.

$$U = H \sigma$$ (8)

The reconstruction of the scene is therefore obtained by solving the following inverse problem:

$$\hat{\sigma} = H^+ U$$ (9)

where $H^+$ stands for the pseudo-inverse operator and where $\hat{\sigma}$ is the estimated reflective function of the scene. This method has the advantage of being analytically comprehensive. However, even if the calculation of the matrix $H^+$ just must be done once for a given reconstruction domain, it requires the manipulation of large matrices, needing the deployment of large computing resources.

2) METHOD 2: EQUALIZATION AND BACK-PROPAGATION
To overcome these computational limitations, a second technique is proposed by splitting the reconstruction presented above into two stages. The objective of this approach is thus to propose an intermediate reconstruction step to estimate the signals $S_f$ received by the antennas. This operation is carried out by equalizing the transfer functions of the receiving channels, computing beforehand the following pseudo-inverse $C^{inv} = C^+$. For each transmitter i and receiver j, the following calculation is performed:

$$\hat{S}_{i,j,f} = U_{i,f} C^{inv}_{j,f}$$ (10)

This operation allows the signals delayed by the different optical fibers to be re-synchronized and compensates for any dispersions and magnitude variations in the pre-characterized transfer functions of the receiving system. A time-gating operation is then performed to only select the time interval corresponding to the unambiguous range of the radar. This window is directly defined by the difference in length between the optical fibers carrying out the time multiplexing. The time-gated signals $\hat{S}_{f,tg}$, expressed in the frequency domain, are then written as follows:

$$\hat{S}_{f,tg} = F(T_g(F^{-1}(\hat{S}_f)))$$ (11)

where $F$ stands for the Fourier transform and $T_g$ is a time-gating function. It is then necessary to define the signals reflected by the scene and actually received by the antennas:

$$\hat{S}_{tg} = G \hat{\sigma}$$ (12)

where $G = G_T G_R$ is a matrix modeling the propagation between all the pairs of transceivers and the space to be imaged. It is finally possible to estimate the response of the target by an ultimate pseudo-inversion operation, which can possibly be substituted by different conventional imaging algorithms:

$$\hat{\sigma} = G^+ \hat{S}_{tg}$$ (13)

This method allows to decrease the reconstruction time by reducing the size of the matrix calculations but requires differentiating the receiving signals.

III. DEVELOPMENT OF THE ELECTRO-OPTICAL TIME MULTIPLEXING SYSTEM
Time multiplexing is a method, most often digital, that enables information from several transmitters to be sent on the same channel. Nevertheless, digital methods impose a complexification of the architecture due to the use of several ADCs. The idea here is therefore to create an architecture that performs this in an analogical way. The first step in time multiplexing is to delay signals in relation to each other. This can be achieved analogously with the help of delay lines of incremental lengths. To ensure time division multiplexing, the difference in propagation lengths must be twice as great as the depth of the region of interest. As the latter is generally in the range of 1 m to 3 m for the targeted applications (body scanning, luggage screening), it seems interesting to use optical fibers to create low loss delay lines. A system is therefore needed to convert the RF signals measured by the receive antennas into optical signals. For this purpose, Mach-Zehnder Electro-Optical Modulators is one of the solutions that can be implemented. These modulators are composed by an optical input where the light is split in two parts. These parts are then modulated in phase with an electrical signal before being re-combined. This combination makes possible to generate an intensity modulated light at the output [32]. The relation between the driving electrical signal and the optical one is a sinusoidal function. In our case to limit the generation
of harmonics at the output, the polarization voltage $V_{DC}$ is chosen equal to $V_{\pi}/2$ where $V_{\pi}$ is the voltage separating a maximum of a minimum from the sinusoidal function. These modulators are placed after each receive antenna. The output optical signals are transmitted to the fibers of different lengths that make up the delay lines array. The information measured with each received antenna therefore lags behind each other.

The second and final step of the time multiplexing consists of summing the optical signals together so that all the receiving information can be acquired on a single reception channel. For this purpose, several solutions exist. The first one is to convert optical signals back to RF signals by using photodiodes (one after each delay line) and then summing them up using a microwave combiner. However, this solution is difficult to implement efficiently. Indeed, even if efforts are made to make broadband RF combiners [33] these are often very lossy. Another solution consists in taking advantage of the optical broadband components. For this purpose, an optical summation using a coupler can be achieved. A single photodiode is then needed to carry out the opto-electronic conversion. Nevertheless, these components have also high optical losses which are proportional to $1/N$, where $N$ is the number of inputs. In addition, the coupler architecture makes possible for the optical signals to interact with each other. A last solution is proposed in [34]. It consists in using an optical concentrator to bring all the signals in front of a single photodiode, while keeping them physically separated from each other, in order to add and convert them at the same time. The concentrator is a microstructured preform with silica (light gray) and air holes (dark gray) in which single mode fibers are inserted (Fig. 2). The entire structure is then stretched to have a useful diameter at the output smaller than the diameter of the photodiode used. During this stretching, the diameter of the single mode fibers decreases. The core therefore gradually loses its guiding power and the wave begins to propagate in the cladding. To limit this effect and prevent the waves of the different single mode fibers from interfering with each other, the fibers are positioned in such a way to keep a ring of air holes around each of them. The Fig. 3 shows the decrease in the diameter of the fiber with the enlargement of the area occupied by the optical signals and, at the end, a limitation of this enlargement due to the presence of air holes. The optical signals are confined from the input to the output of the summing device where they are directly converted into RF signals. The Microwave Photonic Summation Device (MPSD) makes then possible to have in the same time very few losses and to avoid interference issues. This component is then chosen to carry out the summation function in our system.

IV. PRESENTATION OF THE 5.5-7.5 GHz PROTOTYPE

From a more general point of view, the imaging system developed here should allow to interrogate a $0.8 \times 0.8$ m$^2$ region at 1.5 m with a cross range resolution of 5 cm. These performances are achieved by placing 32 Vivaldi antennas (16 for transmission and 16 for reception) in a Mills Cross configuration [35]. The antennas are arranged in a square pattern, placing the transmitters on the horizontal axes and the receivers on the vertical ones, as shown in Fig. 5b. The distance between two consecutive elements is 9 cm (i.e. $2\lambda$). This MIMO configuration permits to create a $1.4 \times 1.4$ m$^2$ virtual array with 256 antennas [36] leading to the expected properties. The Vivaldi antennas being placed in front of a
metal plate, corrugations have been drawn on their edges to limit their rear radiation and thus avoid reconstruction artifacts that would have appeared behind the targets.

Fig. 4 shows the schematic of the transmitting and receiving channels. For the transmitting part, an arbitrary waveform generator is used to generate a 2 GHz bandwidth Gaussian pulse modulating a 2 GHz carrier. The signal is then up-converted by an RF mixer driven by a 4.5 GHz local oscillator, allowing to get an operating bandwidth centered at 6.5 GHz. The signal is therefore transmitted through a high-pass filter to a power amplifier before being routed to each transmit antenna through a SP16T PIN diode switch. The signals transmitted by one antenna and reflected by the imaging scene are received by the 16 receive antennas and amplified by low-noise amplifiers. Once these signals are amplified, they modulate a CW lightwave through Electro-Optical Modulators. The optical signal is delivered by two distributed feedback lasers and transmitted to the modulators with polarization maintaining fibers. Then, the modulated optical signals go through the delay lines array. The incrementation between two consecutive fibers is 6 m, leading to a 30 ns time delay. This opening a maximum unambiguous range of 4.5 m in free-space. These optical delayed signals are added together and re-converted to RF signals using MPSD. They are then amplified by a last LNA, converted to a baseband (1-3 GHz) and transmitted by a low-pass filter to a 20 Gs/s real-time oscilloscope. Eventually, the demultiplexing of the signals and the reconstruction of the radar images are carried out in the numerical layer. Fig. 5a shows the back panel of the scanner with the blue transmitting switching matrix and on each vertical edge the Electro-Optical Modulators.

The characterization of each photonic path was performed by using a VNA connected to a photodiode and by removing the summator. The average RF-loss induced by these paths is equal to $-43$ dB at the central frequency of 6.5 GHz (Fig. 6). A 2 dB RF power difference is observed among all paths due to optical losses such as connectors and optical fiber splitter inhomogeneity. These losses are compensated using the 40 dB LNAs placed before each EOM. The group delay of each photonic channel is also shown in Fig. 7. The difference in propagation time between two consecutive channels is equal to 30 ns, with a maximum variation of up to 2 ns, which correspond to the 6 m fiber length incrementation. These various delays will be considered during the total characterization of the system.

V. MEASUREMENTS
A. SYSTEM CALIBRATION
The two methods exposed in the paragraph II require the measurement of the transfer function of the time multiplexing channels ($C_f(r_f)$) but also of the other RF components, which are not perfect. To perform these measurements a calibration technique is set up. This calibration is carried on by removing the antennas and connecting the transmitting and receiving inputs with a reference cable. The contribution of this cable is compensated in pre-processing. To avoid the tedious measurements of all the TX/RX pairs, only the
FIGURE 7. (a) Group Delay induced by the 16 optical channels with the use of a single distributed feedback laser, (b) Averaging value of the 16 group delays.

Transfer functions of the first transmitting channel towards each receiving channels j and the transfer functions of each transmitters i towards the first receiver are measured. The transfer functions of the individual TX/RX pairs are then calculated as follows:

$$C_{\text{tot}(i,j)} = C_{(1,j)} \times C_{(i,1)}/C_{(1,1)}$$

$$C_{\text{tot}(i,j)}$$ replace the $$C_f(r_s)$$ term in the Eq. 6 and Eq. 10.

B. RESOLUTION AND FOV OF THE SYSTEM

Before studying the impact of the two reconstruction methods, a validation measurement is performed with a single metal sphere of 7 cm of diameter positioned at 1.5 m of the antennas array. This measurement will make it possible to check the resolution and field of view (FOV) of the system. The reconstruction is here performed with the Inversion of the full model method. The Fig. 8a shows the 3D reconstruction of the scene with the target at the center. The aliasing at the edges delimit the FOV. Cross-sections have been extracted from the 3D reconstruction and shown in Fig. 8b and Fig. 8c. These cross-sections are compared with the simulation of a reconstruction of a punctual target positioned at the same place than the sphere (the blue curves show the experimental overcome and the orange ones are for the simulations). The width of the pics representing the targets are similar, showing that the resolution of our system has been reached. This resolution is measured equal to 5 cm, as expected. The measured FOV is also equal to 0.8 by 0.8 m², even if the simulated one is a bit smaller. This difference is due to the fact that the simulation does not take into account the antennas radiating pattern.

FIGURE 8. (a) 3D reconstruction of a sphere positioned at 1.5 m from the array with the Inversion of the full model method, (b) Horizontal cross section extracted at y = 1.5 m and z = 0 m, (c) Vertical cross section extracted at y = 1.5 m and x = 0.015 m. A simulation of a target placed in the same location as the sphere is performed to compare the result obtained with the theoretical resolution limits of this system.

C. STUDY OF THE RECONSTRUCTIONS WITH THE TWO MATHEMATICAL METHODS

A comparison of the two reconstruction methods is performed with a more complex scene. This scene consists in 5 metal marbles positioned in a 50 cm width square pattern. The reconstruction with the Inversion of the full model method (Fig. 9a) and the Equalization and back-propagation method (Fig. 9b) are performed in the targets plan. The targets being considered as punctual, the resulting images are very close from each other and the cross-section in the top two metal marbles (z = 0.2 m) highlight the concordance between the resulting of these two methods (Fig. 9c). The main difference is the time of reconstruction. Indeed, if all the sensing matrices ($$H^+$$ and $$G^+$$) have been pre-calculated the Inversion of the full model requires 1.4 s to reconstruct a scene with 2000 pixels while the Equalization and backpropagation method only needs 0.3 s with a computer
FIGURE 9. 2D reconstructions of 5 metal marbles positioned in a square pattern with the Inversion of the full model method (a) and the Equalization and back-propagation method (b). (c) Comparison of the cross sections of the two reconstructions extracted at \( z = 0.2 \) m.

FIGURE 10. (a)-(d) 2D reconstruction of a scene composed by 5 metallic marbles arranged in a 50 cm width square pattern with 1 marble at its center with a variable number of averages, (e) Study of the PSNR in function of the number of averages.

FIGURE 11. Reconstruction of a complex target: (a) Picture of the target, (b) 3D reconstruction of the scene, (c) Cross-section extracted at \( y = 1.64 \) m of the 3D reconstruction, (d) Phase of the cross-section.

not pre-calculated, the first method reaches 30 s to image the scene and the second method 1 s. As the Equalization and back-propagation method is faster it will be used for the next reconstruction.

D. STUDY OF THE IMPACT OF THE NUMBER OF AVERAGES

During the acquisition of the reflected signal, the number of averages is a main parameter to consider. To study the impact of this parameter several measurements of the previous scene are carried on, and a progressive averaging is applied (Fig. 10).

The Pic Signal to Noise Ratio (PSNR) [37] is calculated between the resulting reconstructions and the simulation of the reconstruction of the scene where the 5 spheres are replaced by 5 punctual targets (Fig. 10d). It is noticeable that from 40 averages the targets become easily recognizable and above 100 averages, the evolution of the PSNR is no longer significant enough to have an impact on the reconstructed image. An animated figure showing the evolution of this image is available in the supplementary materials.

E. RECONSTRUCTION OF A COMPLEX SCENE

The reconstruction of a more complex target is eventually achieved (Fig. 11). This target consists of metal tubes assembled to form the word XLIM. The length of this target is 80 cm and its high is 20 cm. The structure holding this target has equipped with 16 GB of RAM and a four-core 3.3 GHz CPU. The time-gating performed before the calculation of the \( G^+ \) matrix (Eq. 11) permits to reduce the number of frequency points and then decrease the time of reconstruction by a factor 3 for the second method. Moreover, if the sensing matrices are...
a refractive index close to 1, It is therefore invisible at the reconstruction.

A cross-section is extracted from the 3D reconstruction in the target plane (Fig. 11c). A visualization of the phase of this cross section is exposed in Fig. 11d. This visualization shows that there is a difference of $2\pi$ between the left side of the reconstruction and the right side. For the central wavelength approximation, this phase shift corresponds to a $4\pi$ inclination along the depth range of the scene. This inclination is equivalent to an offset of 5 cm between the right and left of the target. This offset is 1.5 times smaller than the range resolution (i.e. 7 cm).

VI. CONCLUSION

In this paper a mathematical study was proposed to explain the physical functioning of a MIMO system with a time multiplexing structure at reception. This study made possible to understand the impact of the optical-time-multiplexing architecture used, on the usual reconstruction methods and then proposed two new algorithm solutions. In addition, explanations concerning the development of this architecture have been proposed. The prototype developed here made it possible to reconstruct 3D scenes with 5 cm of resolution at 1.5 m and a 15 dB dynamic range. These results validate the use of a photonic time division multiplexer in a MIMO architecture. Thanks to this transposition in the optical domain, future work will focus on the exploitation of signal processing functions carried out directly in the physical layer in order to push back even further the frontiers of current solutions.

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