An RF Scanning Receiver based on Photonics for Electronic Warfare Applications

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***Abstract* — We present the design and simulative results of an innovative RF receiver based on photonic techniques that quickly scans the RF band of interest in warfare applications, avoiding the spectrum channelization and thus reducing the receiver SWaP. The scheme is based on a stable mode-locked laser and a specifically designed tunable optical filter, and it simultaneously samples, filters, and down-converts the detected spectrum. The analysis confirms the scheme capability for detecting signals beyond 18GHz, with instantaneous bandwidth >1GHz and dynamic range >40dB. The scheme implementation with integrated photonics technologies will ensure fast scanning (filter repositioning in <100ns), high environmental stability, and reduced SWaP, meeting the increasingly stringent requirements of electronic warfare applications.**

Keywords— Electronic support measures, microwave photonics, mode-locked lasers, tunable optical filter.

I. Introduction

The wideband RF receivers needed in electronic warfare (EW) scenarios should reliably analyze the RF spectrum in the microwave region (typically, 2÷18 GHz). Recently, the rapidly changing nature of the threats is requiring avoiding the noisy RF down-conversions and moving the digital processing directly at RF, in order to enhance the system's flexibility and sensitivity [1]. Nowadays, the bandwidth limitations of current analog-to-digital converters (ADCs) impose a channelized approach, which splits the RF spectrum of interest into narrowband portions to be down-converted and analyzed separately. This approach implies significant size, weight and power requirements (SWaP) for the EW system. An alternative implementation with reduced SWaP is to exploit a single digital receiver that scans the frequency range of interest. For this solution to be applicable, the RF filter and the local oscillator (LO) must have the capability of tuning quickly to the desired frequency, so that each portion of the spectrum can be down-converted and digitized in few hundred milliseconds. Although current RF integrated circuits support operation frequencies exceeding several tens of GHz, RF filters and LOs with similar tunability and tuning speed do not exist yet.

Current photonic technologies offer huge bandwidth, intrinsic electromagnetic immunity, and easy flexibility. In application to the microwave field, photonics is recently demonstrating additional attractive features as ultra-narrowband filters with flat top and steep edges [2], extremely large and fast tunability (several tens of GHz in few ns) [3], small footprint [4], as well as precise down-conversion of RF signals up to tens of GHz [5].

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In this paper we propose, to the best of our knowledge, the first architecture of an RF receiver based on integrated photonics which enables the fast scanning of the wideband RF spectrum through the filtering and down-conversion of the detected spectrum in the optical domain, with an instantaneous bandwidth of few GHz, high precision, and reduced SWaP. A preliminary experimental analysis, based on lumped elements, has already validated the principle of operation of the scheme [6]. Here we report the results of detailed simulations that define the design parameters of the system components and demonstrate the compliance of the proposed RF scanning receiver to the required performance for EW applications.

II. Principle Of Operation

Table 1 reports the main specifications for the RF scanning receiver in EW applications. The receiver must be able to detect RF signals over broad ranges of frequency (2÷18GHz) and input power (-80÷0dBm). The reliability required by the EW application demands for high instantaneous dynamic range (>40dB) and spurious-free dynamic range (SFDR) (>50dB), and low noise figure (NF) (<5dB). Moreover, the need for a continuous monitoring of the entire RF spectrum asks for a rapid scanning of the observation band, with filter tuning time <100ns. The requirements above can be met realizing the following photonics-based basic operations. First, the superior time stability of a mode-locked laser (MLL) and the broad electro-optical bandwidth of photonic devices are exploited to implement a precise direct sampling of the received spectrum.

Table I. Desired and Obtained Performance Values

Figure of Merit	Desired Value	Obtained Value
Input frequency range	2÷18 GHz	2÷18 GHz
Input power range	-80÷0 dBm	-80÷0 dBm
Instantaneous bandwidth	1 GHz	1 GHz
Instantaneous dynamic range	>40 dB	43.5 dB
Spurious-free dynamic range	>50 dB	50 dB
Noise figure	<5dB	<3dB
Band selection time	<100ns	Achievable

Then, the large and fast tunability of an integrated optical filter is used to select a portion of the detected spectrum in the optical domain. Finally, the filtered spectrum is down-converted at baseband taking advantage of the broad tunability and high precision of the photonic heterodyning technique.

The architecture of the proposed photonics-based RF receiver is sketched in Fig. 1. A MLL acts as the only laser source of the scheme. Because the MLL emits a train of optical pulses, its optical spectrum is a comb of phase-locked laser modes with a detuning equal to the MLL repetition rate f_R (inset *i* in Fig. 1). The signal from the MLL is split along two arms after being amplified. On the upper arm, it is amplitude-modulated in a Mach-Zehnder modulator (MZM) by the received RF spectrum (which has been first amplified, and filtered by an anti-alias filter, AAF). This double-sideband modulation copies the received RF spectrum around each mode of the MLL, realizing the optical filtering (inset *ii*). In order to scan the detected RF signal, the upper sidebands (USB) (or, equivalently, the lower sidebands – LSB) of the modulated optical spectrum are filtered by a periodic tunable optical filter (PTOF), the free spectral range (FSR) of which must be equal to f_R (inset *iii*). On the lower arm, the pulses from the MLL are decimated by a factor M in a MZM, creating new phase-locked spectral components with detuning f_R/M (inset *iv*) which are used as a comb of local oscillators (LOs) for down-converting the filtered spectral components. A periodic optical notch filter (PONF) is also inserted, with the same FSR as the MLL, to attenuate the original laser modes (inset *v*) and suppress the spur components due to the limited extinction ratio (ER) of the upper MZM. The optical signals from the two arms are then combined in a hybrid optical coupler (inset *vi*) to realize an in-phase/quadrature (I/Q) detection in two balanced photodiodes (PDs). The electrical signals at the PDs outputs are therefore the down-converted I and Q baseband components of the filtered RF signal (inset *vii*). They are then amplified and digitized by two ADCs, and the selected portion of the RF spectrum is calculated at baseband by a digital signal processor (DSP), also implementing a digital filtering at 1GHz.

The effectiveness of the scheme largely relies on the quality of the MLL and of the periodic optical filters. The stability of the MLL guarantees the accurate down-conversion of the filtered RF spectral window. The recent advances of integrated photonics technologies allow the implementation of specific periodic filters with accurate shape, as will be detailed in the next paragraph, and fast tunability over tens of GHz [3]. Moreover, the realization of the optical RF scanner as a single integrated photonic circuit is expected to guarantee the system resilience to the environmental fluctuations, which is necessary in EW scenarios.

III. Simulative Study

The scheme of Fig. 1 is implemented in a software simulator to finely tune the system design parameters and to study the achievable performance. In the analysis, VPItransmissionMaker is used for simulating the optical architecture. The generation and amplification of the RF signals are managed with Simulink. The ADCs and DSP are emulated through MatLab scripts. Most of the parameters' values are taken from commercial devices. Few non-standard values are also considered, taken from custom devices or reported in scientific literature.

A MLL at 1550nm generating 3ps pulses at f_R=40GHz is taken into account as the laser source, with an output power of 10dBm. The chosen repetition rate allows the correct sampling of the RF range of interest. The MLL here is considered free of jitter and amplitude noise, since a precise modelling of these phenomena would result in a prohibitive computational burden. Instead, jitter and amplitude noise of the MLL are taken into account through separated simplified models. The jitter model suggests that a jitter lower than 15fs (integrating the phase noise for offset frequency from 5kHz on) guarantees a signal-to-noise ratio (SNR) up to 60dB before the ADCs, 10dB higher than the maximum detectable SNR. The amplitude noise model considers the maximum acceptable amplitude fluctuation of the MLL as 10 times smaller than the minimum digitization step of the ADC, setting it to about 0.05%. Commercial MLLs can fulfill both the above requirements. An optical amplifier with a

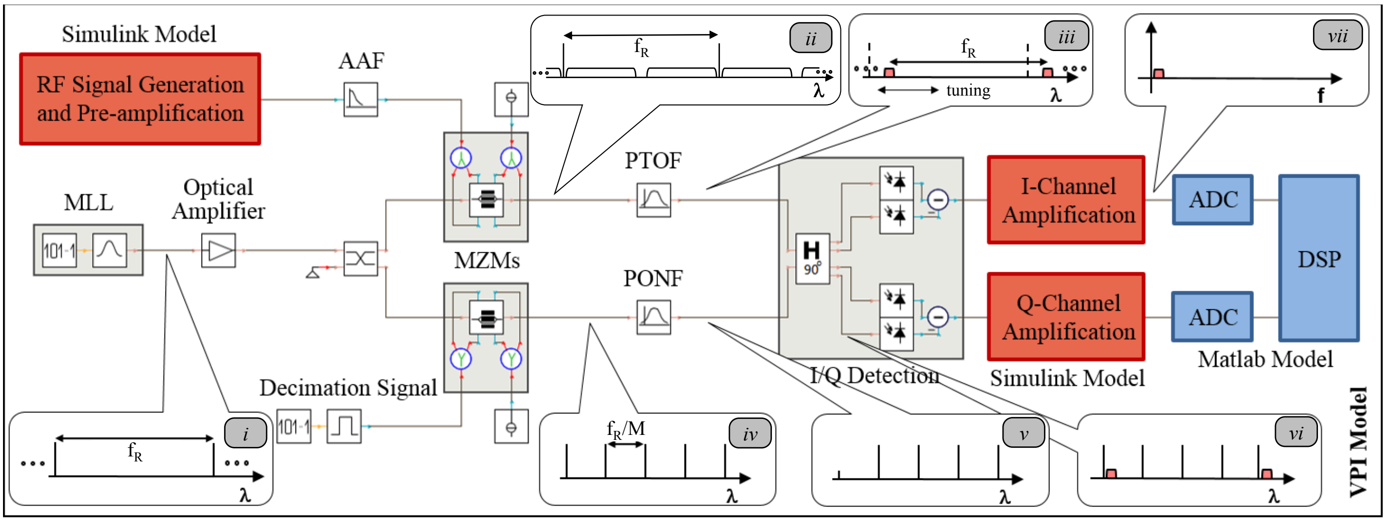

Fig. 1. Architecture of the photonics-based RF scanning receiver. The different development environments for the different parts of the system simulator are also depicted. The insets sketch the optical or electrical spectrum opf the signals in different part of the scheme.

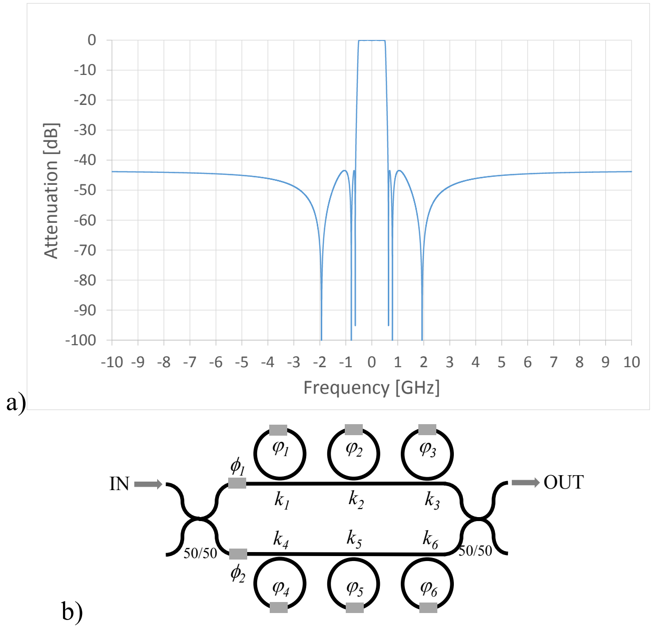

Fig. 2. Simulative results for an optical sixth-order elliptical filter. a) Normalized response of a single filtering window. The filter has a period of 40GHz. b) Filter implementation as a Mach-Zehnder interferometer loaded with six ring resonators, where the controls (coupling coefficients and phase shifts) are highlighted.

NF of 6.5dB is considered after the MLL to boost the optical pulses to 800mW.

Typical parameters are considered for the two MZMs: 40GHz 3dB-bandwidth, 6.4V Vπ, insertion loss 4dB. In particular, the 3dB-bandwidth is large enough both in the upper arm, where a maximum signal frequency of 18GHz is considered, and in the lower arm, where the 40GHz pulse train is decimated by a factor M=32 to 1.25GHz. The extinction ratio of the modulators is particularly important for the receiver performance, therefore the standard value of 22dB is raised to 30dB, which is still an achievable value with custom MZMs by controlling the splitting ratio of the internal interforometer. The balanced photodiodes exploited for the optical I/Q detection need an easily achievable opto-electrical bandwidth >0.5GHz. They also need to work in a linear regime. In the scheme, the optical power at the PDs is considered <3dBm, while a common saturation value is in the order of 10dBm.

The periodic optical filters (both the PTOF and PONF) are the most peculiar components in the architecture, and are non-standard devices. To ensure the maximum efficiency of the scheme (i.e., the minimum NF), the PTOF needs a free spectral range matched with the MLL repetition rate, so that each filtered window can contribute to the generation of the down-converted signal. The filtering windows must have an out-of-band rejection greater than 40dB to guarantee the required instantaneous dynamic range (IDR), and they must be reasonably flat over 1GHz. To match these requirements, a periodic elliptic filter of the sixth order is considered. Fig. 2a reports the shape of the filtering window considered in the simulator, which has been obtained implementing a Mach-Zehnder interferometer loaded with six micro-ring resonators, as sketched in Fig. 2b. A similar filter has been demonstrated in [4]. Correctly setting the coupling coefficients k_i and the phase shifts φ_j, it is possible to obtain a 3dB-bandwidth of 1GHz and very steep edges ensuring a suppression >43.5dB at ±750MHz from the central frequency. The in-band ripples are <1dB. More details on the filter design will be included in the final paper. It is important to underline that micro-rings can be tuned very quickly, down to few ns [3]. In the lower arm of the receiver structure, the PONF needs a FSR of 40GHz as well, an out-of-band rejection >30dB, and a more relaxed edge roll-off.

As it is well known, the effect of the RF pre-amplifier on the system performance is fundamental in terms of NF and SFDR. Thus, an RF dynamicator has been designed cascading RF amplifiers and variable attenuators. The parameters of commercial devices (gain, NF, intermodulation products, etc) are considered, optimizing the dynamicator's design targeting an RF power of 0dBm at the RF port of the upper MZM, while minimizing the system NF and the nonlinearities. Moreover, two amplification stages are considered after the PDs in order to dynamically fit the input voltage range of the ADCs, which are considered to have a dynamic range of +/-1V and an input bandwidth of 1GHz. The ADCs are implemented with 8 bits of ideal resolution, and a sampling rate of 2GSample/s. Finally, the DSP calculates the complex envelop of the filtered and down-converted signal from the digitized I/Q channels.

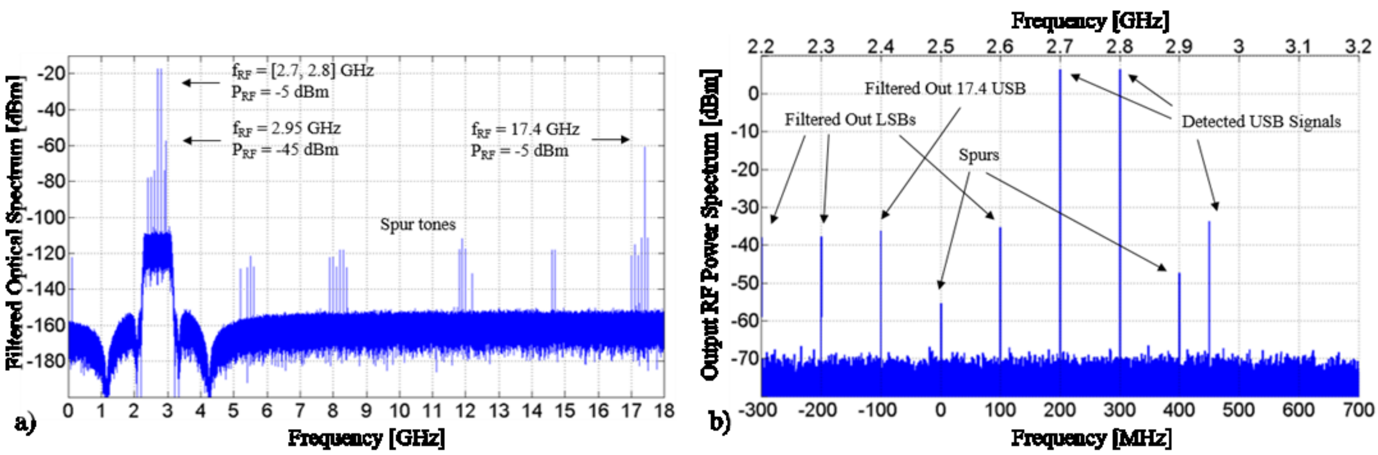

Fig. 3. a) Output optical signal from the PTOF (portion of interest of one period); b) Complex envelope output of the RF scanning receiver. The upper horizontal axis reports the originally detected frequency. The lower axis reports the corresponding down-converted signal frequency.

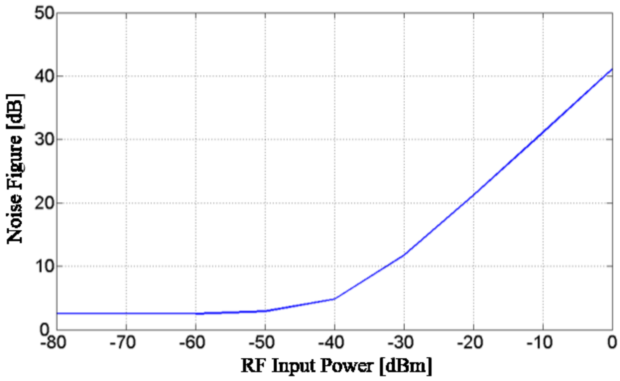

Fig. 4. NF of the optical RF scanning receiver as a function of the RF input power.

In order to analyze the basic function of the optical RF scanner, we consider the case of four input tones: three tones with an RF power of -5dBm at frequency respectively of 2.7GHz, 2.8GHz, and 17.4GHz; and a tone with a power of -45dBm at 2.95GHz. The total RF power at the receiver input is about 0dBm, i.e., the maximum foreseen power. The PTOF is set to select the signal at 2.7GHz. Fig. 3a shows one of the filtered USB from the spectrum of the modulated MLL at the output of the PTOF. The figure only shows the portion from 0 to 18GHz from the original mode of the MLL. Beside the input signals selected within the filter window (at 2.7GHz, 2.8GHz, and 2.95GHz), it is possible to recognize the suppressed signal at 17.4GHz, the original MLL mode at 0Hz, the second and third harmonics generated by the MZM at about 5.4GHz and 8.1GHz, and the intermodulation products generated by the pre-amplifier and by the upper MZM.

The signal reconstructed by the DSP is reported in Fig. 3b. As it can be seen from the upper axis, the graph is centered at 2.7GHz, which corresponds to the central position of the optical filtering window, and spans from 2.2GHz to 3.2 GHz, which is the flat 3dB-bandwidth of the filter response. The corresponding frequencies of the calculated down-converted complex signal are plotted on the lower axis, where the 0Hz corresponds to the LO closest to the filtered spectral region, i.e, to 2.5GHz. The component of the signal at 2.7GHz is clearly detected at the center of the reconstructed spectrum. The signals at 2.8GHz and 2.95GHz are selected by the filter as well, and their power ratios with respect to the central signal are correctly maintained, therefore the requirement of IDR>40dB is satisfied. The signal at 17.4GHz has been attenuated by the filter, and is aliased at -100MHz (since its closest LO is at 17.5GHz), with a suppression of 43.5dB due to the rejection of the optical filter. Few other spurious components are visible, three of which correspond to the strong tones at 2.7, 2.8 and 2.95GHz from the suppressed LSB of the modulated MLL. As can be seen, the requirement for the SFRD>50dB is achieved as well.

The graphs in Fig. 3 reveal that the noise floor of the reconstructed spectrum is sufficiently low to allow the correct signals detection within the required IDR. Considering the case of a single input tone, it is possible to calculate the SNR of the reconstructed signal, and thus the NF of the system. The total NF of the receiver is evaluated as a function of the input RF power, corresponding to different settings of the dynamicator. The obtained NF curve is reported in Fig. 4: a NF<3dB is ensured for input RF power up to -50dBm, overcoming the initial system requirement.

The comparison between the main desired and obtained performance values for electronic warfare applications are summarized in Table 1.

IV. Comments and Conclusion

The proposed RF scanning receiver is based on photonic technologies and allows a precise, fast, and effective scanning of the RF spectrum up to tens of GHz, avoiding the bulky and power-hungry channelized approach. The simulative analysis presented in this work shows the capability of the photonics-based solution in achieving the typical performance required by EW scenarios, as summarized in Table 1. The design of the architecture demonstrates that low time jitter MLLs available on the market, and high-order integrated optical filters realizable by photonic integrated technologies, permit the achievement of the desired performance. The analysis also points out several possible additional improvements. A MLL with higher repetition rate could allow analyzing frequency ranges beyond 40GHz. The repetition rate of the decimated pulses and the 3dB bandwidth of the optical filter could be increased to enlarge the RF instantaneous bandwidth of the system. Moreover, the receiver shows a good sensitivity, with very low noise floor after the detection, thus if a PTOF filter with increased rejection could be designed, the IDR could be increased beyond 40dB. The already planned implementation of the proposed RF scanning receiver by means of photonic integrated technologies is therefore expected to fulfil the most stringent requirements of next EW applications, by both increasing the receiver performance and reducing its SWaP.

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