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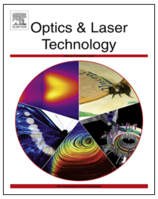

Full length article

Demonstration and experimental evaluation of a bi-directional 10-GHz microwave photonic filter

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ABSTRACT

A bi-directional 10-GHz microwave photonic filter is proposed and experimentally evaluated. Its frequency response consists of a series of microwave band-pass windows obtained by the interaction of externally modulated multimode laser diodes emitting around of 1550 nm associated to the chromatic dispersion parameter of an optical fiber, as well as the length of the optical link. Microwave band-pass windows exhibit on average a-3 dB bandwidth of 378 MHz. This electro-optical system shows an efficient configuration and good performance. Potentially, filtered microwave signals can be used as electrical carriers in optical communication systems to transmit and distribute services such as video, voice and data.

1. Introduction

Owing to the fact that microwave photonic filters (MPFs) allow processing radio frequency (RF) signals by using high-speed photonic devices, they provide a technological alternative to solve some restrictions in the electrical domain, such as limitation by frequency band, sampling frequency speed and precision of signal processing. It is evident that MPFs are a powerful tool allowing the processing of microwave signals directly in the optical domain and offering the advantages of low loss, high bandwidth, immunity to electromagnetic interference, and the capacity to support high sampling frequency [1]. Thanks to these advantages, MPFs find applications in radio-over-fiber systems and radio astronomy [2,3]. Research on MPFs focuses on designing new structure to obtain tunability, reconfigurability and larger bandwidth [4-6]. Considering this scenario, in recent years we proposed a MPF architecture whose frequency response in the range of 0.01–10 GHz consists of four band-pass windows centered at frequencies that can be tailored to the function of the free spectral range (FSR) of a multimode laser diode (MLD), the chromatic dispersion parameter of the optical fiber used, as well as the length of the optical link [7]. It has also been successfully demonstrated [8,9], that the filtered band-pass windows were used as electrical carriers to transmit and distribute signal video finding potential applications in radio-over-fiber systems. Now, the purpose of this paper is to describe a novel approach to implement a bi-directional MPF based on the principle previously cited. In this paper, we demonstrate to the best of our knowledge, this type of architecture. The performance of the proposed bi-directional 10-GHz MPF is validated experimentally. The significant relevance of this work resides in the fact that potentially the filtered band-pass windows can be used as electrical carriers to transmit services such as video, voice, and data. This paper's outline is as follows. In Section 2, we give a brief description of the basic principle of operation of the MPF used. Section 3 describes the experiment that supports the approach here proposed. Finally, the conclusions are summarized in Section 4.

2. Principle of operation

As reported in [7], the frequency response of the MPF depicted in Fig. 1 is determined by the real part of the Fourier transform of the optical spectrum of the optical source used. The interested reader can find a full theoretical analysis of the principle of operation in the reference previously cited. In the following, we give a concise analysis to deduce the parameter that allows determining the central value for each filtered band-pass window.

We consider a MLD as optical source whose emitted light is modulated by a Mach-Zehnder Intensity Modulator (MZ-IM) operated on the linear region with a RF electric signal $V_m = 1 + 2m\cos(\omega_m t)$ of electrical frequency ω_m, where m is the

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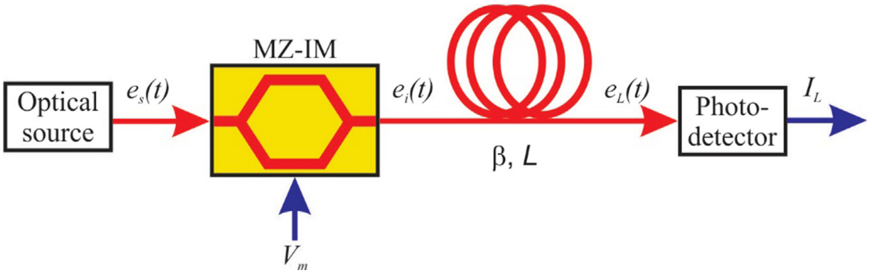

Fig. 1. Basic architecture of the microwave photonic filter [7].

modulation index which is given by $m = \pi\,(\frac{V(t)}{V_\pi})$, where V_π is the half wavelength voltage of the MZ-IM. Assuming the optical fiber as a linear time invariant system characterized by its propagation constant $(\beta)$and its length (L), the received optical signal that impinges to the photo detector produces a detected current that can be expressed as [7,10]

$$I_L = I_0 + m\cos\left(\frac{1}{2}\omega_m^2\beta_2 L\right)\cdot 2\int_0^\infty S(W)\cos(WZ)dW \tag{1}$$

where I_0 is the average intensity of the optical source, $W = \omega - \omega_0$ with $dW = d\omega$, and $Z = \omega_m\beta_2 L$, with $\beta_2 = -D\left(\frac{\lambda_0^2}{2\pi c}\right)$, λ_0 is the central wavelength, D is the chromatic dispersion parameter of the optical fiber, and c is the speed of light in a medium of refractive index n given as $c = \frac{c_0}{n}$, where c_0 is the speed of light in free space. Thus, Eq. (1) can be written as

$$I_L = I_0 + m\cos\left(\frac{1}{4\pi c}\omega_m^2\,\lambda^2\,D\,L\right)\,F.\,T.\,\{S(W)\} \tag{2}$$

Therefore, the frequency response of the MPF is determined by the second term of Eq. (2), which is proportional to the Fourier transform of the spectrum of the optical source. Knowing that, a MLD exhibiting a Gaussian envelope and modes centered at an angular frequency ω_0 can be modeled as [11]

$$S(W) = \frac{2S_0}{\Delta_\omega\sqrt{\pi}}\exp\left(-\frac{4\,(\omega-\omega_0)^2}{\Delta_\omega^2}\right)\cdot\left[\frac{2}{\sigma_\omega\sqrt{\pi}}\exp\left(-\frac{4\,(\omega-\omega_0)^2}{\sigma_\omega^2}\right)*\sum_{n=-\infty}^{\infty}\delta\,(\omega - n\delta_\omega)\right] \tag{3}$$

where S_0 is the maximum power emission, $\Delta\omega$ is the full width at half maximum (FWHM) of the spectrum, σ_ω is the FWHM of each mode, δ_ω is the free spectral range (FSR) between the modes and * denotes the convolution operation. The term between square parentheses corresponds to a train of impulses indicating a periodic pattern. By using variables Z and W, as defined previously, the Fourier transform of Eq. (3) is

$$F\cdot\,T\cdot\{S(W)\} = \exp\left(-\left(\frac{\Delta_\omega Z}{4}\right)^2\right) * \left[\exp\left(-\left(\frac{\sigma_\omega Z}{4}\right)^2\right)\cdot\frac{1}{\delta_\omega}\sum_{n=-\infty}^{\infty}\delta\left(Z - n\frac{2\pi}{\delta_\omega}\right)\right] \tag{4}$$

The location of each impulse determines the central frequency of the nth band-pass filtered in the frequency response of the MPF. If these values are denoted as f_n they can be determined by equating $Z = n(\frac{2\pi}{\delta_\omega})$. Thus, we obtain

$$f_n = n\left(\frac{1}{D\,L\,\delta\lambda}\right) \tag{5}$$

where n is a positive integer (n=1, 2,…), and $\delta\lambda$ is the FSR of the spectrum given in nm. Meanwhile, the associated bandwidth at −3 dB of the nth band-pass window is determined as

$$\Delta f_{bp} = -\frac{4\sqrt{\ln 2}}{\pi\,D\,L\,\Delta\,\lambda} \tag{6}$$

It is evident that the transfer function of the MPF is composed of multiple band-pass windows that depend on the spectral profile of the MLD, on the chromatic dispersion value of the optical fiber, and on its length.

3. Experimental evaluation

In a first step, by means of an optical spectrum analyzer (Agilent, model 86143B) we have optically characterized the two MLDs used in this experiment. Hereafter referred to as MLD_1 and MLD_2. MLD_1 (Thorlabs, model S1FC1550) at an optical power of 1.25 mW reveals: $\lambda_0 = 1536.05$ nm, $FWHM(\Delta\lambda) = 6.15$ nm, and $\delta\lambda = 1.1$ nm, whereas MLD_2 (Thorlabs, model LPS-1550-FC), at an optical power of 1.21 mW exhibits: $\lambda_0 = 1547.2$ nm, $FWHM(\Delta\lambda) = 7.31$ nm, and $\delta\lambda = 1.1$ nm It is important to remark that the use of a temperature-controller allows us to operate the laser diodes with a well-stabilized injection current, assuring in this way the stability of the optical parameters to thermal fluctuations and by consequence a low value of relative intensity noise (RIN) [12].

Once the optical characteristics are verified and established the conditions of operation, the proposed bi-directional 10-GHz MPF set-up illustrated in Fig. 2 is assembled.

It is important to highlight that the frequency range available for the microwave signal generators (MSGs) used in this experiment is 0.01–20.0 GHz for MSG_1 (Anritsu, Model MG3692), and 250 kHz–3.0 GHz for MSG_2 (Agilent, Model E4425B). In the following, a detailed description of the experimental procedure is given for two cases.

Case 1. MSG_1 is used to feed the Mach Zehnder-Intensity Modulator (MZ-IM_1) in order to modulate the optical signal that travels from left to right, whereas MSG_2 is employed to feed the Mach Zehnder-Intensity Modulator (MZ-IM_2) with the aim of modulating the optical signal that travels from right to left. The light issued by MLD_1 is injected into the optical isolator (OI) in order to avoid reflections and to guarantee the stability of the optical source. Since the MZ-IM is polarization-sensitive, a polarization controller (PC) is used to maximize the modulator output power. The lightwave is intensity-modulated via MZ-IM_1 (Photline, model MXAN-LN-20, insertion loss of 2.7 dB, $V\pi = 5.5\ V$, operating wavelength 1530–1580 nm) in the frequency range of 0.01–10 GHz at 5 dBm and $V_{bias} = 2.97\ V$. The modulated optical signal is injected to Port 1 of OC_1 passing to Port 2 where it is