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Microwave photonic filter tuning by varying the optical link length

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Abstract—Experimental tuning of a microwave photonic filter is achieved by varying the optical link length. Filtering effect is obtained by the interaction of an externally modulated multimode optical source and a dispersive channel. Experimental transmission of TV-signal using this filter is also described in this paper.

I. INTRODUCTION

Microwave photonics allows processing high-frequency signals directly in the optical domain, thus exploiting the large bandwidth, low loss and immunity to electromagnetic interference inherent to optical systems [1]. Moreover, it is desirable that microwave filters be tunable. This feature allows wide flexibility to the filters because its frequency response can be tuned at specific desired frequencies. In this sense, several works have been reported for implementing tunable microwave photonic filters: by using variable optical delay lines [2], [3], by combining tunable lasers and dispersive optical devices [4], [5], by tuning chromatic dispersion combined with fixed optical wavelengths [6], or by using chirped fiber Bragg gratings [7]. All these works use various devices which in turn increases the complexity and cost of the systems. On the other hand, we reported [8] a novel setup which relies on the use of a multi-longitudinal mode laser diode (MLLD) associated with the channel chromatic dispersion and the optical link length, and thus reducing the complexity and cost. Now, this work is supported by the results previously reported in [8] where the main originality resides in the tuning of filtered microwave signals by using an appropriate optical link length. A series of experiments are achieved in the frequency range of 0.01 to 8 GHz for demonstrating the tuning of the filter. To show a potential application of this system in the field of optical telecommunications, an experimental transmission of TV-signal coded on filtered microwave signals located at 1.92 and 3.85 GHz is carried out. For this purpose, a 28.30 km single mode standard fiber (SMSF) and an MLLD emitting at an optical wavelength of 1537.44 nm are used. This scheme

demonstrates an interesting alternative for transmitting information using optoelectronics techniques with potential applications in the field of fiber-to-the-home (FFTH) and fiber-to-the-building (FTTB) network architectures. After this introduction, this paper is organized as follows: in Section II, the principles of filtering and tuning of microwave signals are introduced. Section III is devoted to describing in detail numerical simulations as well as experimental setups. Finally, conclusions are summarized in Section IV.

II. PRINCIPLE OF OPERATION

The basic schematic diagram of the microwave photonic filter used in this work is shown in Fig. 1. Its frequency response is determined by the real part of the Fourier transform of the MLLD emission spectrum. Its frequency response is composed of a low-pass band and multiple harmonic band-pass windows. The low-pass response of the system is centered at zero frequency. The center frequency of the n -th harmonic band-pass window is determined by

$$f_n = \frac{n}{DL\delta\lambda} \quad (1)$$

where n is a positive integer ($n = 1, 2, \dots$), D ($\text{ps}\cdot\text{nm}^{-1}\text{km}^{-1}$) is the optical fiber chromatic dispersion, L (km) is the optical link length and $\delta\lambda$ (nm) is the free spectral range (FSR) between two adjacent longitudinal modes in the MLLD emission spectrum. As can be seen from (1), the n -th band-

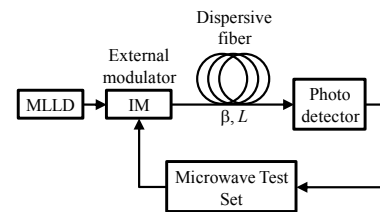


Figure 1. Microwave photonic filter [8].

pass window is centered at a resonance frequency which is an integer multiple of the first central frequency, f_1 . Therefore, the most straightforward technique for tuning the band-pass windows is varying the value of L . This affirmation is validated in the next section, where optical link lengths of 20.70 km, 28.30 km and 50.70 km are used.

III. SIMULATION AND EXPERIMENTAL RESULTS

This section is divided in three subsections. In a first step, numerical simulations to evaluate the microwave photonic filter frequency response are shown. Next, experimental setups that allow filtering and tuning of microwave signals are described. Finally, experimental TV-signal transmissions, using filtered microwave signals as electrical carriers, are shown.

A. Numerical simulations

In order to demonstrate filtering and tuning effects, three simulations were carried out. Parameters corresponding to the MLLD and SMSF are listed in Table I. Simulations were performed by evaluating (1) and computing the Fourier transform of a given optical spectrum. Expression (2) allows modeling an optical spectrum corresponding to a MLLD with a Gaussian envelope

$$P(\lambda) = \frac{2P_0}{\Delta\lambda\sqrt{\pi}} \exp\left(-\frac{4(\lambda - \lambda_0)^2}{\Delta\lambda^2}\right) \times \left[\frac{2P_0}{\sigma\lambda\sqrt{\pi}} \exp\left(-\frac{4(\lambda - \lambda_0)^2}{\sigma\lambda^2}\right) * \sum_{-\infty}^{\infty} \delta(\lambda - n\delta\lambda) \right], \quad (2)$$

where λ is the wavelength, P_0 is the maximum power emission, λ_0 is the peak wavelength, $\Delta\lambda$ is the full width at half maximum (FWHM) of the optical source, $\sigma\lambda$ is the FWHM of each emission mode, $\delta\lambda$ is the FSR between the emission modes, n is a positive integer ($n = 1, 2, \dots$) and $*$ stands for convolution. Figures 2 (a) and (b) illustrate an

TABLE I. PARAMETERS FOR SIMULATIONS AND EXPERIMENTS

Parameter	Simulation/ Experiment 1	Simulation/ Experiment 2	Simulation/ Experiment 3
SMSF L	20.70 km	28.30 km	50.70 km
MLLD λ_0	1553.85 nm	1537.44 nm	1553.85 nm
MLLD $\delta\lambda$	1.00 nm	1.15 nm	1.00 nm

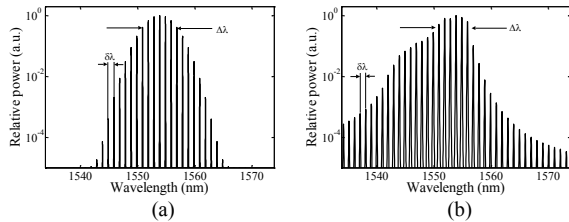


Figure 2. Optical spectra. (a) Generated by using (2). (b) Recorded by means of an optical spectrum analyzer (OSA).

optical spectrum obtained by using (2), and by means of an optical spectrum analyzer (OSA), respectively. Simulations were carried out using any of these spectrums.

Chromatic dispersion is the most critical parameter when evaluating (1). For this reason it is crucial to know the real value of this parameter. In this sense, expression (3), obtained from a third-order Sellmeier equation, allows evaluating the real dispersion value due to the corresponding wavelength [9]

$$D(\lambda) = \frac{\lambda S_0}{4} \left[1 - \left(\frac{\lambda_x}{\lambda} \right)^4 \right], \quad (3)$$

where $S_0 = 0.084169 \text{ ps}\cdot\text{nm}^{-2}\text{km}^{-1}$ is the slope of $D(\lambda)$ at a wavelength $\lambda_x = 1300 \text{ nm}$, which is the zero dispersion wavelength for SMSF. By using (3), the chromatic dispersion parameter was evaluated for $\lambda = 1537.44 \text{ nm}$, and $\lambda = 1553.85 \text{ nm}$, obtaining $D = 15.81 \text{ ps}\cdot\text{nm}^{-1}\text{km}^{-1}$ and $D = 16.67 \text{ ps}\cdot\text{nm}^{-1}\text{km}^{-1}$, respectively.

Dotted curves in Fig. 3 illustrate results of simulations of

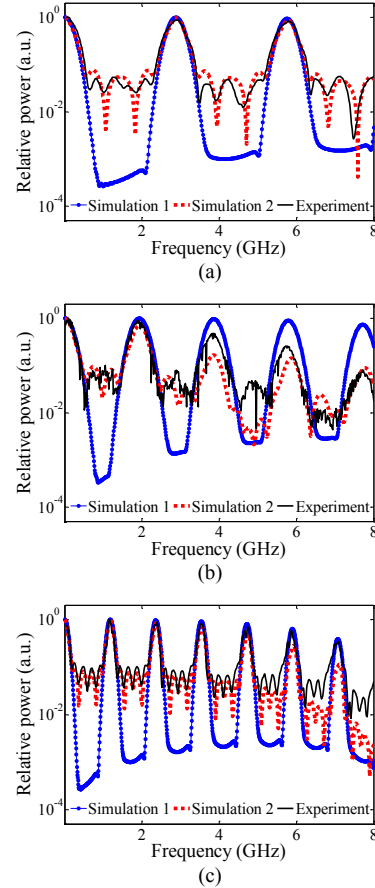


Figure 3. Simulation and experimental results. Simulation 1 was carried out using an ideal numerical spectrum, while Simulation 2 was carried out using a real optical spectrum. (a) $L = 20.70 \text{ km}$, $D = 15.81 \text{ ps}\cdot\text{nm}^{-1}\text{km}^{-1}$ and $\delta\lambda = 1.00 \text{ nm}$. (b) $L = 28.30 \text{ km}$, $D = 16.67 \text{ ps}\cdot\text{nm}^{-1}\text{km}^{-1}$ and $\delta\lambda = 1.15 \text{ nm}$. (c) $L = 50.70 \text{ km}$, $D = 15.81 \text{ ps}\cdot\text{nm}^{-1}\text{km}^{-1}$ and $\delta\lambda = 1.00 \text{ nm}$

the frequency response of the system carried out using a spectrum generated by using (2). For each case, the corresponding L , D and $\delta\lambda$ values have been considered. A better matching between simulation and experimental results was obtained when simulations were carried out taking into account a real optical spectrum. Dashed curves in Fig. 3 correspond to such simulations. From these graphs, it is clearly seen that if the dispersive optical link length is increased, then the central frequencies of the band-pass windows are shifted at lower frequencies.

B. Filtering and tuning of the microwave signals

In order to demonstrate the tuning and filtering effects, three experimental setups were assembled. The corresponding parameters are listed in Table I. The base setup used in these experiments is shown in Fig. 4. At the output of the MLLD an optical isolator (OI) was used for avoiding reflections to the cavity, and a polarization controller (PC) was employed for controlling the phase. The optical signal was launched into a Mach-Zehnder intensity modulator (MZ-IM). The microwave electrical signal for modulating the optical intensity was supplied by a vector signal generator (VSG). The intensity-modulated optical signal was then launched into a SMSF coil. Finally, the optical signal was applied to a fast photo-detector (PD), and its electrical output was then measured by an electrical spectrum analyzer (ESA). For Experiments 1 and 3, the utilized components were: an Oki OL5200N-5 MLLD ($\lambda_0 = 1553.8$ nm and $\delta\lambda = 1.00$ nm), a Photline MX-LN-10 MZ-IM, and a Miteq DR-125G-A PD, whereas for Experiment 2, the used components were: a Mitsubishi ML95B6F MLLD ($\lambda_0 = 1537.44$ nm and $\delta\lambda = 1.15$ nm), a

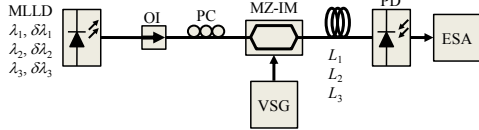


Figure 4. Experimental setup assembled for tuning the frequency response of the system by varying the optical link length.

JDS-APE AM-150 MZ-IM, and a Miteq DR-125G-A PD.

Solid curves in Fig. 3 correspond to experimental results. It is noticeable that location of resonance frequencies obtained by simulations match to those obtained in experimental way. A considerable mismatch in the frequency response of the systems obtained in an experiment versus a simulation can be due to the uncertainties in the parameters used for evaluating (1) [10]. Finally, Table II summarizes the theoretical, simulated and experimental values corresponding to the resonance frequencies. These results ensure that several modulation schemes can be used for transmitting multiplexed information by using microwave photonic filters, which have multiple harmonic band-pass transmission windows.

C. Experimental transmission of TV-signal

To show potential applications in the field of optical telecommunications, the system was used for transmitting and recovering analog TV-signal. The experimental setup is illustrated in Fig. 5. Transmissions were realized using the conditions given for the Experiment 2 (see Table I). Microwave electrical signals tuned at 1.92 and 3.85 GHz, corresponding to the central frequencies of the first and second band-pass windows of the frequency response of the system, were used as electrical carriers. In the first case a 1.92 GHz microwave signal issued from the VSG, was mixed with an analog NTSC TV-signal of 61.25 MHz (TV channel 3). The resulting mixed electrical signal was applied to the MZ-IM for modulating the optical intensity. The modulated optical signal was launched into the dispersive optical fiber coil (28.30 km) and finally photo-detected. In the second case, the only

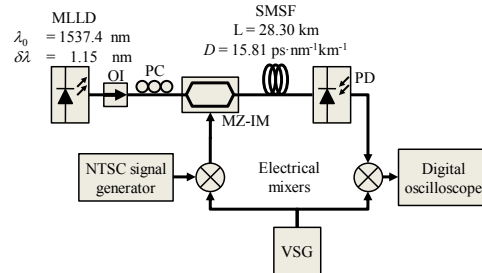


Figure 5. Experimental setup for transmitting and recovering analog TV-signal.

TABLE II. THEORETICAL, SIMULATED AND EXPERIMENTAL RESONANCE FREQUENCIES.

	$L_1 = 20.70$ km			$L_2 = 28.30$ km			$L_3 = 50.70$ km		
	$\lambda_1 = 1553.86$ nm			$\lambda_2 = 1537.44$ nm			$\lambda_3 = 1553.86$ nm		
	$D_1 = 16.67$ ps-nm ⁻¹ km ⁻¹			$D_2 = 15.81$ ps-nm ⁻¹ km ⁻¹			$D_3 = 16.67$ ps-nm ⁻¹ km ⁻¹		
	$\delta\lambda_1 = 1.00$ nm			$\delta\lambda_2 = 1.15$ nm			$\delta\lambda_3 = 1.00$ nm		
	Theo	Sim	Exp	Theo	Sim	Exp	Theo	Sim	Exp
f_1 (GHz)	2.89	2.86	2.90	1.94	1.91	1.92	1.18	1.16	1.18
f_2 (GHz)	5.79	5.72	5.80	3.88	3.83	3.84	2.36	2.33	2.38
f_3 (GHz)	---	---	---	5.82	5.75	5.73	3.54	3.50	3.50
f_4 (GHz)	---	---	---	7.77	7.67	7.73	4.73	4.67	4.71
f_5 (GHz)	---	---	---	---	---	---	5.91	5.85	5.84
f_6 (GHz)	---	---	---	---	---	---	7.09	7.03	7.03

Theo: Theoretical; Sim: Simulated; Exp: Experimental

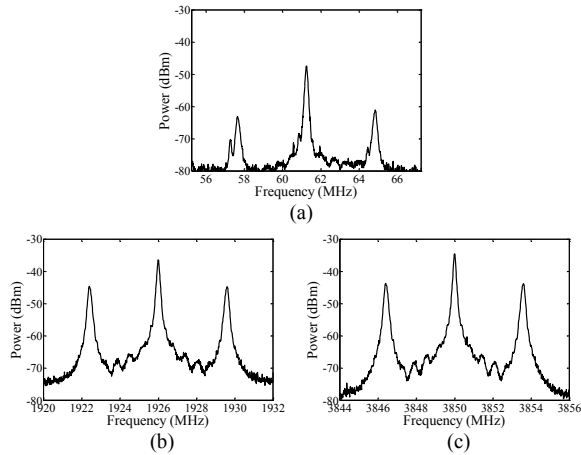


Figure 6. Power spectrums. (a) Transmitted NTSC signal spectrum. (b) Detected spectrum at 1.92 GHz. (c) Detected spectrum at 3.85 GHz.

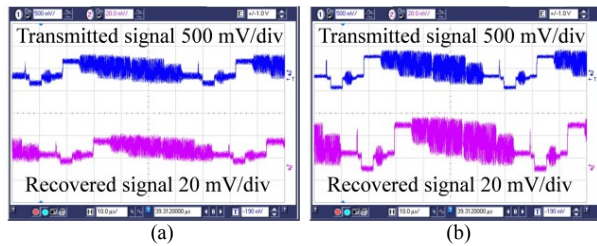


Figure 7. Oscilloscope screens displaying transmitted and recovered TV-signal, (a) at 1.92 GHz, and (b) at 3.85 GHz.

difference was the signal frequency issued by the VSG (3.85 GHz, in this case). NTSC signal power spectrum is shown in Fig. 6(a), whereas Fig. 6(b) and Fig. 6(c) illustrate the photo-detected signals power spectrums, for transmissions at 1.92 and 3.85 GHz, respectively. Power of detected signals is higher due to the photo-detector gain. Finally, from Fig. 7(a) and 7(b) signal-to-noise-ratio (SNR) parameter was evaluated for the recovered signal corresponding to transmissions at 1.92 GHz and 3.85 GHz obtaining 12.54 dB, and 11.72 dB, respectively. In this way, experimental transmission of information was carried out using two different band-pass windows of the frequency response of the system. Under the same operation principle, the other band-pass windows can be used for transmitting tuned microwave subcarriers.

IV. CONCLUSIONS

A novel tunable optical microwave band-pass filter using appropriate optical link lengths was proposed and experimentally demonstrated. Filtering of microwave signals was supported by the use of chromatic fiber-dispersion parameter, the length of the optical link, and the free spectral range of the multi-longitudinal mode laser diode. Tuning was

achieved by varying the length of the optical link. This technique allows having a full reconfigurable electrical transfer function. We have conducted some experiments in order to verify the validity of this technique and we have obtained a good agreement between the theoretical and experimental results. Simulations of the frequency response of the system were carried out using ideal numerical optical spectrums and recorded real optical spectrums. Finally, in order to show an application on the field of optical telecommunications, TV-signal was successfully transmitted on the microwave-signal filtered at 1.92 and 3.85 GHz. In this case, the microwave-signal acts as an electric carrier. Due to the gain of the used photo-detector, electrical amplification stages were not necessary. The transmission was tested and the TV-signal was recovered without noticeable quality degradation.

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