Demonstration of a Duplex Microwave Photonic Filter and Its Reconfigurability in a Frequency Range of 0–10 GHz

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Abstract: In this paper, we have demonstrated a duplex microwave photonic filter system. The reconfigurability of a microwave passband filter by using a birefringent optical filter has also been demonstrated experimentally. The effect of filtering normally depends on the intermodal separation of a multimode laser diode (MLD), as well as the chromatic dispersion parameter and the length of a Single Mode-Standard Fiber (SM-SF). However, in this work, the intermodal separation of the MLD is altered by an optical filter which consists of a section of birefringent optical fiber (BOF) placed between crossed polarizers. Using this filter, six passbands in the frequency range of 0–10 GHz are obtained. Our duplex Microwave Photonic Filter (MPF) system is driven by only a single optical source. Performance evaluation for the filtered passband is also given in terms of the Signal-to-Noise-Ratio (SNR). On average, an SNR of 13.87 dB is obtained for all the passbands generated by our duplex Microwave Photonic Filter (MPF) system. For potential applications, the generated passbands may be used as radio frequency (RF) carriers to transmit analog or digital data in an optical communications system.

Keywords: microwave photonic filter; microwave signals; optical system communication; electro-optical devices

1. Introduction

A microwave photonic filter (MPF) is defined as a photonic system designed for carrying out equivalent tasks to those of an ordinary electrical microwave filter within a radio frequency (RF) system. An MPF provides benefits innate to photonics, such as low loss, high bandwidth, immunity to electromagnetic interference (EMI), tunability, and reconfigurability [1–3]. These benefits make them a technology whose main application is to assign frequency bands; as a consequence, one of its applications is in the field of optical communications. In particular, tunability and reconfigurability are topics of interest in terms of the versatility of MPFs. To date, some approaches to achieve tunability and reconfigurability have been reported. For instance, in [4] an MPF with two different passbands is proposed. The center frequency of these two passbands is tuned by changing the free spectral range (FSR) of a Mach Zehnder Interferometer (MZI) through an optical tunable delay line (OTDL). In Ref. [5], a multipassband MPF based on multiple dispersive devices is also demonstrated, generating four
frequency passbands. An MZI formed by a variable optical delay line (VODL) allows simultaneous tuning of the center frequencies of the passbands by adjusting the VODL. In [6], a highly selective and stable MPF with two independently tunable passbands is reported. The dual-passband MPF is based on phase-to-intensity modulation conversion by Stimulated Brillouin Scattering (SBS) and the tuning is achieved in the frequency range of 0–9.644 GHz. The bandwidth of the passband is approximately 45 and 55 MHz when the MPF is working in gain mode and loss mode, respectively.

In this work, we propose a duplex MPF with reconfigurable passbands. On the one arm of our duplex system, the first MPF generates a fixed frequency passband. On the other arm, the second MPF performs with six configurable frequency passbands. The duplex MPF architecture is implemented by using a multimode laser diode (MLD) emitting at 1550 nm, a Mach Zehnder-Intensity Modulator (MZ-IM), an optical link of Single Mode-Standard Fiber (SM-SF), and a fast photodetector (PD). Here, it is important to highlight the use of the chromatic dispersion parameter exhibited by optical fibers, as well as the length of the optical fiber as key parameters to generate the frequency bands of an MPF. The reconfigurability is achieved by the use of an adequate optical filter that allows changing the intermodal separation (δλ) of the MLD. For this purpose, we have used a section of Birefringent Optical Fiber (BOF) in order to introduce an optical delay [7,8]. Thus, by adjusting δλ with the BOF, the reconfigurability of the MPF is demonstrated with six passbands experimentally. The generated passbands are evaluated in terms of Signal-to-Noise-Ratio (SNR). The results indicate that the generated microwave passband signals may be used as electrical carriers to transmit analog or digital data in an optical communication system.

Organization of the Document

The rest of this paper is organized as follows. The operation principle of the MPF used in this work is described in Section 2. The simulation and experimental results on the filtering by using a section of BOF are given in Section 3. Finally, a brief discussion and conclusions are given in Section 4.

2. Principles of Operation

In our previous study [9], we have reported that the scheme shown in Figure 1 can be used as an optical filter that allows varying the intermodal separation (δλ) of an MLD. This intermodal separation variation is carried out by choosing the adequate length (LBF) of the birefringent fiber (BF). The light emitted from the MLD passes across the section of BF placed between two crossed polarizers. The output of this filter is observed on the optical spectrum analyzer (OSA).

![Figure 1. Schematic diagram of an optical filter. MLD: multimode laser diode; PC: polarization controller; BOF: birefringent optical fiber; OSA: optical spectrum analyzer [9].](image)

We were obtained the graph illustrated in Figure 2 from [9]. A length of $L_{BF1} = 2.53$ m of BOF exhibits a refractive index difference of $\Delta n_1 = 4.7 \times 10^{-4}$ (blue line), leading to an intermodal separation of $\delta \lambda$ of around 2 nm. Similarly, for a length of $L_{BF2} = 2.0$ m of BOF, the refractive index difference is obtained as $\Delta n_2 = 8.1 \times 10^{-4}$ (red line) and the intermodal separation $\delta \lambda$ is expected to be near 1.3 nm. Readers can be referred to [9] for details.

Since the reconfigurability of the MPF is based on the filtering of the spectrum of the MLD, it is important to know its optical characteristics. Thus, first, the MLD used throughout these experiments was optically verified. In order to ensure its stability to thermal fluctuations, the MLD was driven at 25 °C by a temperature-controller and operated with a well-stabilized injection current of 80 mA.
At this injection current, the optical power of the MLD was measured as 11 mW. Figure 3 depicts the measured power–current curve (L–I curve) of the MLD.

**Figure 2.** Variation of the intermodal separation as a function of the fiber length [9].

**Figure 3.** Power–current (L–I) curve of the MLD.

Figure 4 shows the optical spectrum recorded by means of an Optical Spectrum Analyzer (OSA, Anritsu, model MS9740A, range 600 nm to 1750 nm, high resolution of 0.03 nm (1550 nm band). In the figure, the center wavelength and the intermodal separation of the MLD are measured as \( \lambda_0 = 1543.89 \text{ nm} \) and \( \delta \lambda = 0.36 \text{ nm} \), respectively.

**Figure 4.** Optical spectrum of the MLD at an injection current of 180 mA.
In order to demonstrate the reconfigurability of our MPF system, the optical filter shown in Figure 1 will be used with the $L_{BF} = 2.53$ m long BOF. The filter with this BOF modifies the optical spectrum of the MLD illustrated in Figure 5. It is clearly seen from the figure that the intermodal separation has successfully been changed from $\delta \lambda = 0.36$ nm to $\delta \lambda' = 1.80$ nm. This demonstrates an additional modulation of the diode laser mode.

![Figure 5. Optical spectrum filtered with a 2.53 m long BOF.](image)

Now, the newly obtained optical spectrum will be exploited to demonstrate the reconfigurability of the MPF.

3. Simulation and Experimental Results

Figure 6 shows the schematic diagram of the proposed duplex MPF system. This setup is composed of two arms. Note that the optical filter mentioned above (dotted box) is placed on the upper arm. On the other hand, the lower arm does not include an optical filter. The optical emission of the MLD is splitted into two by an optical coupler (OC_1). The injection current of 80 mA remains fixed and stable as the laser emission feeds the two arms. First, the operation of the lower arm is given, then the operation of the upper arm will be described.

![Figure 6. Schematic setup of the duplex Microwave Photonic Filter (MPF) system. MLD: multimode laser diode; PC: polarization controller; BF: Birefringent Fiber; MZ-IM: Mach Zehnder-Intensity Modulator; SM-SF: Single Mode-Standard Fiber; PD: photodetector; VOA: Variable Optical Attenuator; OSA: Optical Spectrum Analyzer; MSG: microwave signal generator; ESA: electrical spectrum analyzer.](image)

Lower branch: First, the corresponding frequency response in the range of 0–10 GHz was obtained in a simulation using VPIphotonics software [10]. The simulation parameters of the MLD are $\lambda_0 = 1543.89$ nm and $\delta \lambda = 0.36$ nm. A length of $L = 25.28$ km of SM-SF exhibiting $\alpha = 0.22$ dB/km and...
The electrical signal is amplified by an RF amplifier (700 MHz to 18 GHz, 26dB-gain), and analyzed by the light is modulated by a continuous RF signal supplied by MSG_1 from 0.01 GHz to 10 GHz at an electrical power of 10 dBm. The intensity-modulated light wave travels through a spool of 25.28 km of SM-SF_1 (α = 0.22 dB/km, D = 15.81 ps/nm-km @ 1550 nm). The beam light that emanates at the output of the optical link is converted to an electrical signal by PD_1 (BW = 13 GHz and α = 0.22 dB/km). The experimental operation is described in the following. The splitted laser light passes through PC_1 in Figure 6. Afterward, a VOA is placed in order to adjust the optical power injected into MZ-IM_1 (a bandwidth of 20 GHz, an insertion loss of 2.7 dB, Vπ = 3.0 V, operating at 1530 nm–1580 nm). The light is modulated by a continuous RF signal supplied by MSG_1 from 0.01 GHz to 10 GHz at an electrical power of 10 dBm. The intensity-modulated light wave travels through a spool of 25.28 km of SM-SF_1 (α = 0.22 dB/km, D = 15.81 ps/nm-km @ 1550 nm). The beam light that emanates at the output of the optical link is converted to an electrical signal by PD_1 (BW = 13 GHz and ℜ = 0.9 A/W). The electrical signal is amplified by an RF amplifier (700 MHz to 18 GHz, 26dB-gain), and analyzed by ESA_1, to visualize the MPF response in the frequency domain. Figure 8 corresponds to the measured RF spectrum. One well-formed passband at a center frequency of 7.18 GHz was clearly observed. This passband exhibited a bandwidth of 624.71 MHz at −3 dB, and an SNR of 27.56 dB. The formation of a low passband at the origin of the curve is in good agreement with the theory described in [7].

Figure 7. Frequency response of the MPF on the lower arm simulated by VPIphotonics [10].

The center frequency of this filtered passband is also computed with the formula described in Ref. [7]

\[ f_n = \frac{n}{D \Delta \lambda} \]  

By substituting the \( \delta \lambda \), \( L \), and \( D \) values in the relationship, a value of \( f_1 = 6.95 \text{ GHz} \) was computed.

The experimental operation is described in the following. The splitted laser light passes through PC_1 in Figure 6. Afterward, a VOA is placed in order to adjust the optical power injected into MZ-IM_1 (a bandwidth of 20 GHz, an insertion loss of 2.7 dB, Vπ = 3.0 V, operating at 1530 nm–1580 nm). The light is modulated by a continuous RF signal supplied by MSG_1 from 0.01 GHz to 10 GHz at an electrical power of 10 dBm. The intensity-modulated light wave travels through a spool of 25.28 km of SM-SF_1 (α = 0.22 dB/km, D = 15.81 ps/nm-km @ 1550 nm). The beam light that emanates at the output of the optical link is converted to an electrical signal by PD_1 (BW = 13 GHz and ℜ = 0.9 A/W). The electrical signal is amplified by an RF amplifier (700 MHz to 18 GHz, 26dB-gain), and analyzed by ESA_1, to visualize the MPF response in the frequency domain. Figure 8 corresponds to the measured RF spectrum. One well-formed passband at a center frequency of 7.18 GHz was clearly observed. This passband exhibited a bandwidth of 322 MHz at −3 dB, and an SNR of 17.71 dB. In this case, the low passband was not created due to the bandpass of the electrical amplifier used.

Figure 8. Radio frequency (RF) spectrum measured at the output of the lower arm.
Upper branch: Again, a simulation was carried out by using VPIphotonics software. As mentioned before, the upper arm includes an optical filter which modifies the intermodal separation of the MLD to $\delta \lambda = 1.80 \text{ nm}$. The parameters $L$, $\alpha$, and $D$ remain the same as the ones on the lower arm. Figure 9 shows the simulated frequency response in which seven passbands were clearly observed: $f_1 = 1.36 \text{ GHz} \ (\text{BW} = 296 \text{ MHz}, \text{SNR} = 15.30 \text{ dB}), f_2 = 2.79 \text{ GHz} \ (\text{BW} = 356 \text{ MHz}, \text{SNR} = 10.15 \text{ dB}), f_3 = 4.16 \text{ GHz} \ (\text{BW} = 355 \text{ MHz}, \text{SNR} = 10.15 \text{ dB}), f_4 = 5.56 \text{ GHz} \ (\text{BW} = 326 \text{ MHz}, \text{SNR} = 14.56 \text{ dB}), f_5 = 6.92 \text{ GHz} \ (\text{BW} = 386 \text{ MHz}, \text{SNR} = 17.65 \text{ dB}), f_6 = 8.35 \text{ GHz} \ (\text{BW} = 326 \text{ MHz}, \text{SNR} = 15.45 \text{ dB}),$ and $f_7 = 9.72 \text{ GHz} \ (\text{BW} = 326 \text{ MHz}, \text{SNR} = 15.45 \text{ dB})$ (the values between parentheses correspond to their corresponding bandwidth and SNR value). Again, a low passband at the beginning of the curve is formed. The corresponding Free Spectral Range (FSR) is 1.43 GHz.

![Figure 9. RF spectrum at the output of the upper arm simulated by VPIphotonics [10].](image)

The experimental description is given in the following. The light splitted by OC_1 is injected into the optical filter (dotted box) with a BOF of 2.53 m-long. The light at the output of PC_3 is splitted into two by another optical coupler (OC_2). One of the outputs of OC_2 is connected to the OSA in order to monitor the optical spectrum of the optical filter. By adjusting the polarization controllers (PC_2 and PC_3), an optical spectrum as shown in Figure 5 is observed on the OSA. The other output of OC_2 is launched to MZ-IM_2 (an insertion loss of 5.0 dB, $V_\pi = 6 \text{ V}$, operating wavelength 1540–1560 nm). A continuous RF signal supplied by MSG_2 in the frequency range from 0.01 GHz to 10 GHz at an electrical power of 10 dBm, is applied to the RF port of MZ-IM_2 to modulate the light. After that, the modulated light wave goes through a spool of 25.22 km of SM-SF_2 ($\alpha = 0.22 \text{ dB/km}, D = 15.81 \text{ ps/nm-km} @ 1550 \text{ nm}$). The beam light that emerges at the end of the optical link is converted to an electrical signal by PD_2 (BW = 13 GHz, and $R = 0.9 \text{ A/W}$). An electric amplifier (700 MHz to 18 GHz, gain 26 dB) supplies an acceptable gain. Finally, the electrical signal is plugged into ESA_2 to observe the RF spectrum of the MPF. Figure 10 shows the measured frequency response compose by six well-formed filtered passbands centered at: $f_1 = 1.28 \text{ GHz} \ (\text{BW} = 296 \text{ MHz}, \text{SNR} = 15.30 \text{ dB}), f_2 = 2.68 \text{ GHz} \ (\text{BW} = 356 \text{ MHz}, \text{SNR} = 10.26 \text{ dB}), f_3 = 4.10 \text{ GHz} \ (\text{BW} = 355 \text{ MHz}, \text{SNR} = 10.15 \text{ dB}), f_4 = 5.49 \text{ GHz} \ (\text{BW} = 326 \text{ MHz}, \text{SNR} = 14.56 \text{ dB}), f_5 = 6.84 \text{ GHz} \ (\text{BW} = 386 \text{ MHz}, \text{SNR} = 17.65 \text{ dB}),$ and $f_6 = 8.19 \text{ GHz} \ (\text{BW} = 326 \text{ MHz}, \text{SNR} = 15.45 \text{ dB})$ (the quantities between parentheses indicate their corresponding bandwidth and SNR values). The FSR of the MPF is 1.40 GHz. A small seventh passband is also observed at $f_7 = 9.55 \text{ GHz}$ but, this passband is discarded in the analysis of results.

Again, the center frequency of each filtered passband is calculated by substituting the values: $\delta \lambda = 1.80 \text{ nm}, L = 25.22 \text{ km},$ and $D = 15.81 \text{ ps/nm-km}$ in Equation (1). For $n = 1, 2, \ldots, 7$, we obtain: $f_1 = 1.39 \text{ GHz}, f_2 = 2.78 \text{ GHz}, f_3 = 4.17 \text{ GHz}, f_4 = 5.57 \text{ GHz}, f_5 = 6.96 \text{ GHz}, f_6 = 8.35 \text{ GHz},$ and $f_7 = 9.75 \text{ GHz},$ respectively.
Finally, Table 1 summarizes the theoretical, simulated, and experimental values corresponding to the center frequencies of each filtered passband. The error percentage among the simulated and experimental center frequencies is tabulated, as well as, the bandwidth and experimental SNR values.

![RF spectrum measured at the output of the upper arm.](image)

**Figure 10.** RF spectrum measured at the output of the upper arm.

**Table 1.** Summary of results.

| Frequency response | Location | Error Percentage | Experimental Δf–3 dB (MHz) | Experimental SNR (dB) |
|--------------------|----------|------------------|-----------------------------|-----------------------|
| to the lower arm   |          |                  |                              |                       |
| $f_1$              | 6.95     | 7.02             | 7.18                         | 2.27                  | 322                  | 17.71               |
| $f_2$              | 1.39     | 1.36             | 1.28                         | 5.88                  | 296                  | 15.30               |
| $f_3$              | 2.78     | 2.79             | 2.68                         | 3.94                  | 356                  | 10.26               |
| $f_4$              | 4.17     | 4.16             | 4.10                         | 1.44                  | 355                  | 10.15               |
| $f_5$              | 5.57     | 5.56             | 5.49                         | 1.25                  | 326                  | 14.56               |
| $f_6$              | 6.96     | 6.92             | 6.84                         | 1.15                  | 386                  | 17.65               |
| $f_7$              | 8.35     | 8.35             | 8.19                         | 1.91                  | 326                  | 15.45               |
| Average            |          |                  |                              |                       | 2.59                 | 340.83              | 13.87               |

### 4. Discussion and Conclusions

We have proposed and experimentally demonstrated a highly selective and stable duplex passband MPF. The effect of filtering is defined by the intermodal separation of an MLD, as well as the chromatic dispersion parameter and length of an SM-SF. The reconfigurability of the frequency response of the MPF is based on altering the intermodal separation of the MLD by filtering its optical spectrum. A section of BOF placed between crossed polarizers was used as an optical filter. The proposed duplex passband MPF is driven by a single optical source of which the optical power is sufficient to drive the two arms without optical amplifiers. Simulations using VPIphotonics software were carried out to validate our proposal. Whereas the frequency response of one arm is composed of only a passband, the frequency response of the other arm is composed of six passbands, tunable in the frequency range of 0–10 GHz. This last confirms the good reconfigurability of the MPF. The quality of the passbands filtered by our MPF system has also been evaluated in terms of signal-to-noise-ratio (SNR). The filtered passband signal exhibited on average an SNR of 13.87 dB and a bandwidth of 340.83 MHz. This value of SNR guarantees that the filtered passbands are well-defined and exempt from noise. These passbands can be used as microwave carriers for transmission of voice, data, and analog signals as demonstrated recently in [11]. An added value of the proposed duplex passband MPF resides in the fact that every arm is driven by its own microwave signal generator (MSG), allowing in this way
an independent operation for the transmission of information. Even more, this proposal of duplex passband MPF has an easy to extend reconfigurability to vary the length of the BOF.

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