Reconfigurable Microwave Photonic Filter Using Multiwavelength Erbium-Doped Fiber Laser

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***Abstract*—A microwave photonic filter using a simple and novel multiwavelength erbium-doped fiber laser (EDFL) is proposed. The filter was experimentally demonstrated featuring tunability and reconfigurability by adjustment of the output from the EDFL. The experimental results show excellent agreement with the numerical simulations.**

***Index Terms*—Microwave photonic filter (MPF), multiwavelength erbium-doped fiber laser (EDFL), signal processing.**

I. Introduction

MICROWAVE photonic filter (MPF) is a powerful technique for implementing signal processing functions of microwave signals [1]–[11]. It offers the advantages of low loss, wide bandwidth, tunability, and reconfigurability. Current implementations of the MPF mainly use a single incoherent light source with coherent time smaller than the minimum delay time of the filter to ensure stable filter operation [1]–[3]. However, its performance is limited by phase induced intensity noise. In addition, delay tuning can be difficult which limits the reconfigurability of the filter. Multisource MPF offers much promise. However, finding a suitable light source has been a challenge. Previous demonstrated schemes in this direction include the use of independent lasers operating at different wavelengths [4], spectrum slicing the output of a broadband source [5], [6], and the use of output spectrum of an Fabry–Pérot (F-P) laser [7]. The main problem associated with the first approach is the high cost when a large Q-value is to be achieved. Spectrum slicing will introduce large amplitude noises. Variation of mode power distribution in the F-P laser has limited its usefulness in filter implementation. Although there was an attempt of using multiwavelength laser for the implementation of MPF, the limited performance of the laser has limited the performance of the MPF filter [8].

In this letter, we demonstrate, for the first time to our knowledge, the implementation of MPF using a multiwavelength erbium-doped fiber laser (EDFL). Due to the ability of the EDFL for stable large number of multiwavelength lasing, large Q can be realized. In addition, the value of Q can be varied through adjustment of the number of output wavelengths from the EDFL. The experimental results show excellent agreement with the theoretical prediction.

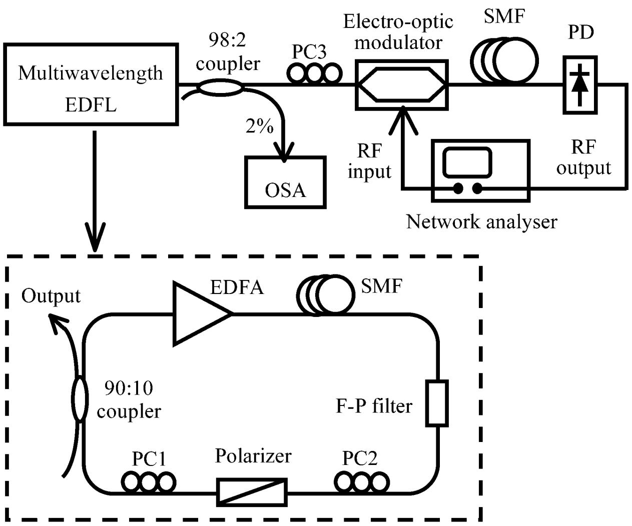

Fig. 1. Diagrams of the filter and the mutiwavelength EDFL.

II. Experimental Setup and Principle

The configuration of the proposed MPF is shown in Fig. 1. The optical taps are generated by a multiwavelength EDFL which has a fixed wavelength spacing of 0.8 nm between adjacent optical taps. The setup of the multiwavelength EDFL is also shown in the same figure. A novel negative feedback control mechanism has been used to ensure stable multiwavelength operation of the laser as reported in [12]. The number of output wavelengths and the output wavelength of the multiwavelength EDFL can be varied by adjustment of the polarization controllers (PCs) in the EDFL ring cavity, which result in the reconfigurability of the filter. Ninety-eight percent of the output from the multiwavelength EDFL is externally modulated using an electrooptic modulator by the microwave signal from a network analyzer. PC3 is used before the modulator for optimum modulation performance. The modulated optical signal is then transmitted through a 25-km-long conventional single-mode-fiber (SMF) coil, which acts as a wideband dispersive medium. Alternatively, other dispersive elements such as dispersion-compensation fiber or tunable chirped fiber Bragg grating (FBG) can be used in place of the SMF. The SMF shows a chromatic dispersion of about 18 ps/nm/km at 1550 nm, which provides an accumulated dispersion of 450 ps/nm. The modulation frequency was swept from 10 MHz to 6 GHz while maintaining a constant output power. The corresponding output of the photodiode is observed

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by the network analyzer. Note that 2% of the output from the multiwavelength EDFL is directly sent to an optical spectrum analyzer for the optical spectrum monitoring.

The filter amplitude transfer function for an equally spaced N -tap transversal filter using a conventional optical amplitude modulation and assuming an optimum polarization adjustment is given by [2]

$$|H_{\rm RF}(f)| = R\cos\left(\frac{\beta f^2}{2}\right)\left|\sum_{k=1}^{N} P_k e^{-j[2\pi f(k-1)\Delta\tau]}\right| \quad (1)$$

where f is the electrical frequency, R is the photodiode responsivity, β is the dispersion parameter, P_k is the optical power of source k, N is the number of the optical wavelengths, and $\Delta\tau$ is the time delay between the optical carriers due to the dispersive medium.

From (1), the filter can be easily reconfigured by tuning the optical sources. The value of the Q-factor is related to the number of taps used to implement it, and the Q-factor can be approximated for uniform filters by the number of taps $Q \cong N$ if the number of the taps is high (>10) [11]. Therefore, Q can be varied by changing the number of taps, i.e., the number of the output wavelengths of the EDFL. Moreover, the frequency of the filter can be tuned by adjustment of $\Delta\tau$. The adjustment of $\Delta\tau$ can be implemented by either changing the output wavelengths of the EDFL or by using a variable dispersive element. Since the multiwavelength laser can be tuned over a wide range (from 1549 to 1600 nm) [12], and the dispersion for different wavelengths is different (which allows $\Delta\tau$ to be varied by proper tuning of the central wavelengths of the EDFL), the proposed transversal MPF is tunable.

III. RESULTS AND DISCUSSION

By adjusting the output from the multiwavelength EDFL, different filter responses could be obtained. Fig. 2 shows one typical transfer function of the filter and the corresponding output spectrum of the multiwavelength EDFL. As shown in Fig. 2(a), very good agreement is observed between experimental results (solid line) and calculated results from (1) by considering the 13 optical modes with tap weighting of $\{0.1, 0.7, 0.95, 1, 1, 1, 1, 1, 1, 0.95, 0.75, 0.6, 0.1\}$ (dashed line). Both experiment and theoretical results give a free-spectral range of ~2.78 GHz and a Q-factor of ~11 (corresponding to the number of the lasing wavelengths with higher and uniform power). Since the output spectrum has some windowing effect, the measured main to secondary sidelobe ratio (MSSR) is better than 20 dB.

Next we addressed the issue of the filter reconfiguration and tunability. Since the number of output wavelengths from the EDFL can be varied by simple adjustment of the PCs in the laser ring cavity, the Q-factor can be changed accordingly.

Fig. 3(a) gives two typical filter responses with a Q-factor of 9 (solid lines) and 25 (dashed lines), respectively, while the central frequency is fixed at about 2.88 GHz. In fact, a maximum Q-factor of 38 has been achieved in the experiment, but with an MSSR of only ~9 dB. The output wavelengths of the EDFL can also be tuned over a wide wavelength range, which shows the possibility of frequency tuning of the filter, as discussed in Section II. Fig. 3(b) gives two typical filter responses with a central frequency of 2.988 (solid line) and 2.638 GHz (dashed line), respectively, giving a tuning range of about 350 MHz. The MSSR in both cases are better than 20 dB. More flexible frequency tuning can be realized by keeping the laser wavelength fixed while changing the dispersion of a variable dispersive element.

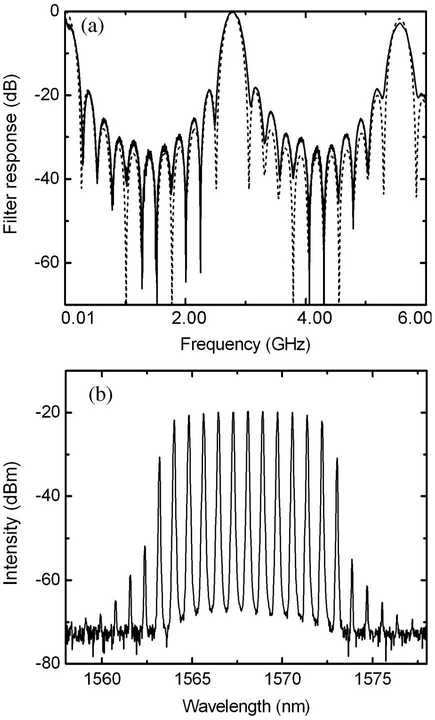

Fig. 2. (a) Experimental (solid line) and simulated (dashed line) filter response and (b) corresponding output spectrum of the EDFL.

When performing frequency tuning by varying the lasing wavelengths of the EDFL, the shape of the filter response also changes slightly, as can be seen from Fig. 3(b). This likely arises from the fact that as the laser is tuned, the number of wavelengths varies as does the power distribution.

For Q larger than 25, there was some noticeable reduction of MSSR. This is because when the number of output wavelengths is large, there are too many wavelengths sharing the limited laser cavity gain, the power of each wavelength is rather weak and the amplified spontaneous emission is not strongly suppressed. Furthermore, the power distribution is not as uniform as that under less wavelength operation.

Further improvement of the MPF can be realized by using the multiwavelength laser with arrayed waveguide/variable optical attenuator or circulator/FBG array configuration with balanced optical detector. Here the output wavelengths from the EDFL can be demultiplexed, attenuated, or amplified on an individual basis, enabling the coefficients of the MPF to be changed. In this case, negative taps, bandpass or high-pass filtering could be possibly achieved by manipulating the filter coefficients.

IV. CONCLUSION

We have proposed and demonstrated an MPF using a novel multiwavelength EDFL. The output wavelength and the number

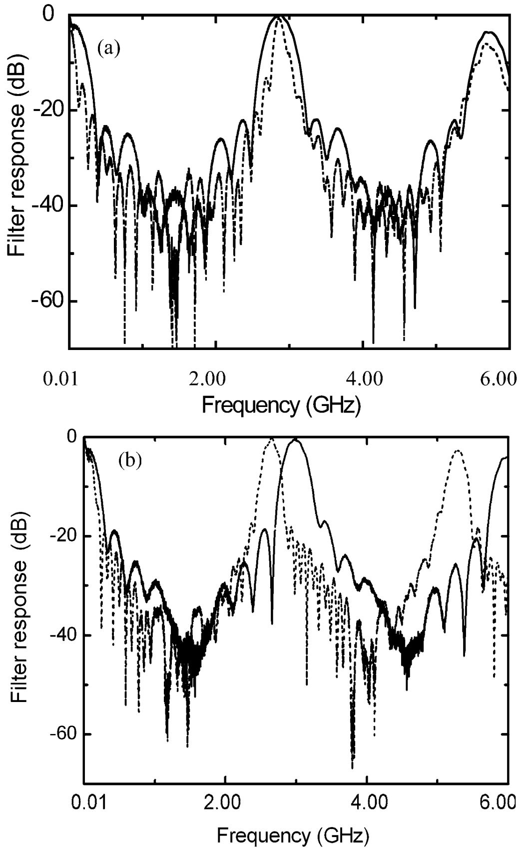

Fig. 3. Reconfiguration of the filter. (a) Q-factor adjustment: $Q \cong 9$ (solid line) and $Q \cong 25$ (dashed line); (b) frequency tuning: $f \cong 2.988$ GHz (solid line) and $f \cong 2.638$ GHz (dashed line).

of wavelengths from the EDFL can be varied by adjusting the PCs in the laser cavity. As a result, frequency tuning and variation of the taps number (value of Q-factor) can be achieved.

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