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Tunable Photonic Microwave Band-pass Filter with High-resolution Using XGM Effect of an RSOA

Won-Bae Kwon[1], Chung Ghiu Lee[2], Dongjun Seo[3], and Chang-Soo Park[3]*

[1]Honam Research Center, Electronics and Telecommunications Research Institute (ETRI),
Gwangju 61012, Korea
[2]Department of Electronic Engineering, Chosun University, Gwangju 61452, Korea
[3]School of Electrical Engineering and Computer Science, Gwangju Institute of Science and Technology (GIST),
Gwangju 61005, Korea

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We propose and experimentally demonstrate a simple tunable photonic microwave band-pass filter with high resolution using a reflective semiconductor optical amplifier (RSOA) and an optical time-delay line. The RSOA is used as a gain medium for generating cross-gain modulation (XGM) effect as well as an optical source. The optical source provides narrow spectral width by self-injection locking the RSOA in conjunction with a partial reflection filter with specific center wavelength. Then, when the RSOA is operated in the saturation region and the modulated recursive signal is injected into the RSOA, the recursive signal is inversely copied to the injection locked optical source due to the XGM effect. Also, the tunability of the passband of the proposed microwave filter is shown by controlling an optical time-delay line in a recursive loop.

Keywords : Photonic microwave filter, High resolution, Reflective semiconductor optical amplifier (RSOA), Cross-gain modulation (XGM), Injection locked optical source
OCIS codes : (120.2440) Filters; (350.4010) Microwaves; (060.4510) Optical communications; (070.1170) Analog optical signal processing

I. INTRODUCTION

Photonic microwave filters have attracted considerable interest as an alternative to conventional electrical filters for microwave and millimeter-wave signal processing because they have several advantages such as wide bandwidth, immunity to electromagnetic interference (EMI), tunability, and reconfigurability. Some of these advantages are inherited from the optical processing of microwave signals. These filters can be easily achieved by combining input signal and each time-delayed signal by each tap [1-5].

In particular, for some applications such as radar and universal mobile-telecommunication systems, photonic microwave band-pass filters are required to have high resolution [6, 7]. To achieve high resolution, it can be implemented with finite impulse response (FIR) filters with many taps or infinite impulse response (IIR) filters using a recursive optical delay line. In the case of the FIR filters with many taps, a number of optical sources are required, because the number of taps is determined by the number of optical sources. However, compared with the FIR filter with many taps, the IIR filter is composed of a few optical sources and a recursive delay line, so it can be implemented with a simple structure [8-10]. Moreover, IIR filters with a large number of optical taps can provide high-Q band-pass filtering.

To implement a photonic microwave band-pass filter with high resolution, an IIR filter using fiber Bragg gratings (FBGs) has been demonstrated [8]. The filter has a recursive delay-line structure consisting of two FBGs with different reflectivity, an erbium doped fiber used as an active fiber, and a pumping diode, but phase-induced intensity noise

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*Corresponding author: csp@gist.ac.kr, ORCID 0000-0002-0130-6648

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(PIIN) occurring in the optical tapped delay-line structure becomes the dominant noise source. Recently, to reduce the PIIN in the IIR filters, IIR filters using the cross-gain modulation (XGM) effect inside a semiconductor optical amplifier (SOA) have been reported [9, 10]. However, those filters require an additional gain medium and optical source for generation of the XGM effect and probing, respectively.

In this paper, we propose and experimentally demonstrate a simple tunable photonic microwave band-pass filter with high resolution using a reflective semiconductor optical amplifier (RSOA) and an optical time-delay line. The proposed photonic microwave band-pass filter has a simple recursive loop without additional laser for XGM, where the RSOA acts as a gain medium for optical probing and XGM, simultaneously.

When the bias current is sufficient for the RSOA to operate in the saturation region, the RSOA connected to the FBG acts as an optical source with narrow spectral width. The FBG connected to the RSOA is used as a partial reflection filter. As the modulated recursive signal is injected into the RSOA as a pump light, the data pattern of the probe light generated from the RSOA is inversely copied to the recursive signal due to the XGM effect. In addition, the passband of the proposed filter can be varied by changing the time delay in the recursive loop using an optical time-delay line. By exploiting the RSOA as a gain medium and a probe source, the proposed filter provides the high-Q filtering and the tunability of its passband.

The paper is organized as follows. Section 2 explains the operational principle of the proposed photonic microwave filter. Section 3 describes the experimental setup and measurement results to validate the operation of the proposed filter. The paper concludes with Section 4.

II. OPERATING PRINCIPLE

Figure 1 shows the schematic diagram of the proposed filter using the RSOA. The RSOA has high gain and high XGM conversion efficiency at low current compared to the conventional SOA, because the RSOA has high reflective coating on one side and anti-reflective coating on the other side [11].

The RSOA at dc bias without any injected optical power has a broad spectrum. In order to obtain two wavelength peaks from the RSOA, We need two optical input signals: one for self-injection locking and the other for injection locking by the pump signal. For self-injection locking, we place a partial reflection filter #1 with the center wavelength of λ_{probe} in front of the RSOA. Then, the broad spectrum initially produced is filtered by the spectral width of the filter and fed back to the RSOA. As a result, the RSOA produces an optical signal with the narrow spectral width centered at λ_{probe} [12]. Also, the RSOA is locked to the pump signal. Finally, the RSOA shows two wavelength peaks at λ_{probe} and λ_{pump}.

When the RSOA is operated in the saturation region, the data pattern of the modulated pump signal is inversely copied to the probe light (CW light) due to the XGM effect. These two signals (λ_{probe} and λ_{pump}) pass through the filter #1 due to partial transmission for the probe wavelength and full transmission for the pump wavelength.

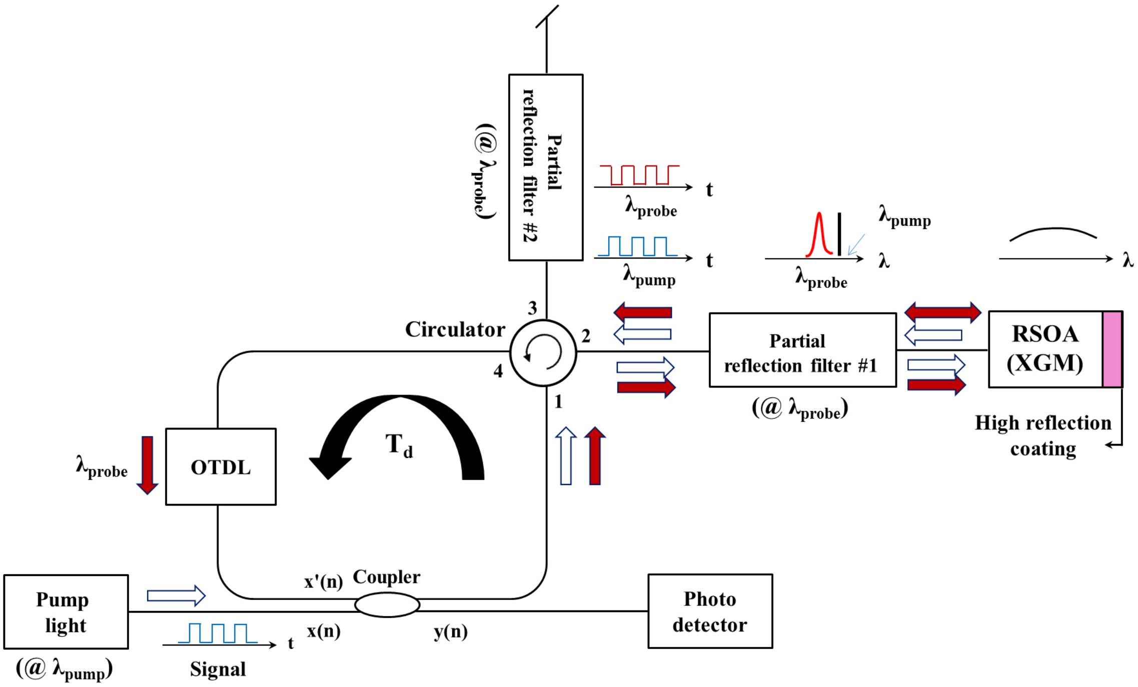

FIG. 1. Schematic diagram of the proposed filter using the RSOA.

To remove the pump signal and control the amount of the probe signal entering the loop, the second partial reflection filter #2 is used and the pump signal is terminated there. The probe signal reflected enters the loop through the circulator, passes through the optical time-delay line (OTDL), and combines with the modulated pump signal at the 2 × 2 coupler. Some portion of each optical signal is coupled to the photo-detector and other portion reenters the recursive loop to achieve the following recursive taps for next delay through the XGM effect in the RSOA.

In the proposed filter, the output is obtained by summing two signals into the coupler, which is given in [9] by

$$y(n) = k \cdot x(n) + (1-k) \cdot x'(n), \tag{1}$$

where $x(n)$ is the modulated pump signal, $x'(n)$ is the recursive signal from the optical source with the center wavelength of λ_{probe} and k is the coupling ratio of the coupler.

The CW light of the self-injection locked optical source generated by the RSOA connected to the partial reflection filter #1 is modulated by the sum of two signals, which are the input signal $x(n-1)$ carried on the pump light and the recursive signal $x'(n-1)$ from the RSOA. The modulation is performed by the XGM effect in the RSOA. The recursive signal $x'(n)$ obtained by the XGM effect can be represented by

$$\begin{aligned} x'(n) = {} & \eta_{12} \cdot T_1 \cdot R_2 \cdot l \cdot g \cdot (1-k) \cdot x(n-1) + \eta_{22} \cdot , \\ & T_1 \cdot R_2 \cdot l \cdot g \cdot k \cdot x'(n-1) \end{aligned} \tag{2}$$

where T_1 and R_2 are the transmittance and reflectivity of the partial reflection filters #1 and #2, l and g are the optical loss and optical gain in the recursive delay loop, η_{12} and η_{22} represent the XGM conversion efficiencies of the XGM effect in the RSOA for converting an RF signal from λ_1 to λ_2 and from λ_2 to λ_2, respectively.

Thus, the transfer function of the proposed filter can be represented by applying *z*-transform to the combined equation of Eqs. (1) and (2), and is given by

$$H(z) = k \cdot \frac{z + T_1 \cdot R_2 \cdot l \cdot g \cdot \left\{k \cdot (\eta_{12} - \eta_{22}) + \frac{1}{k} \cdot (1-2k) \cdot \eta_{12}\right\}}{z - T_1 \cdot R_2 \cdot l \cdot g \cdot \eta_{22} \cdot k}, \tag{3}$$

where $z = \exp(j2\pi f T_d)$, f is the modulation frequency, $T_d = (nL/c) + \triangle T_{OTDL}$ is the time delay corresponding to the recursive loop length L and the optical time-delay line $\triangle T_{OTDL}$, n is the refractive index of the fiber, and c is the speed of the light. In Eq. (3), there is one pole at $T_1 R_2 l g \eta_{22} k$ and the band-pass filter with high resolution can be achieved as the pole approaches the unit circle in the transfer function.

The passband of the proposed microwave filter can be tuned by controlling the time delay in the recursive loop using the optical time-delay line because the modulation frequency is inversely proportional to the time delay of the recursive loop in Eq. (3).

III. EXPERIMENTAL SETUP AND RESULTS

Figure 2 shows the experimental setup of the proposed photonic microwave band-pass filter. A laser diode (LD) with a center wavelength of 1549.8 nm was used as a pump light. The pump signal was modulated by a Mach-Zehnder

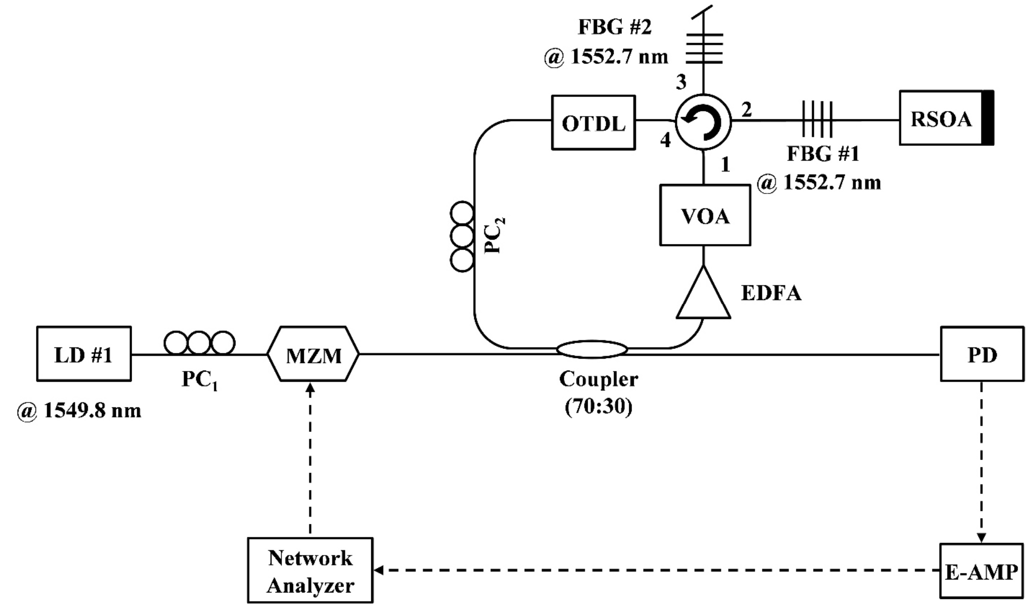

FIG. 2. Experimental setup of the proposed photonic microwave filter.

modulator (MZM) with the RF signal swept from 1 GHz to 1.01 GHz using a network analyzer, and it passed through the 2 × 2 coupler. The coupling ratio of the 2 × 2 coupler was 70:30.

The lasing light with narrow spectral width was produced by self-injection locking the RSOA connected to the FBG #1 with the center wavelength of about 1552.7 nm. The FBG #1 was used as the partial reflection filter at the center wavelength of 1552.7 nm. The reflectivity and full width at half maximum (FWHM) of the FBG #1 were 35% and 0.2 nm, respectively. To optimize the wavelength conversion efficiency in the RSOA, the optical power of the pump light was controlled by the erbium-doped fiber amplifier (EDFA) and the variable optical attenuator (VOA). The amplified pump light was injected into the RSOA via a circulator. At this time, the generated self-injection locked optical light was also injected into the RSOA. The bias current of the RSOA was injected at about 65 mA to satisfy the saturation condition for the XGM effect. To extract the self-injection locked light inversely modulated by the XGM effect, the FBG #2 with the center wavelength of about 1552.77 nm was used as an optical band-pass filter. The reflectivity and FWHM of the FBG #2 were 99% and 0.15 nm, respectively. Also, in the proposed filter, the optical time-delay line was used to tune the passband of the microwave filter.

Figure 3 shows the measured optical spectrum of the self-injection locked light generated from the RSOA measured using an optical spectrum analyzer (OSA). The center wavelength and the 3 dB spectral width of the generated optical source were 1552.77 nm and 0.045 nm, respectively. The side mode suppression ratio (SMSR) of the optical source was larger than 46 dB.

To confirm the 180° RF phase shift induced by the XGM effect in the RSOA, a sine wave was applied to the modulator from the signal generator. The output from port 3 of the circulator contains the original sine wave and its inverted one modulated by the original (non-inverted) sine wave. To separate them, a tunable optical band pass filter was connected to port 3 of the circulator. The separated sine waves were observed as shown in Fig. 4.

Figure 5 shows the frequency response of the proposed photonic microwave filter. The solid line represents the measured values from the experiment and the dotted line represents the simulation result. The free spectral range (FSR) of the proposed filter was about 2.65 MHz and the maximum stopband rejection level of the filter was about 34 dB. The Q-factor of the filter was 81. Compared to the previous microwave band-pass filter using the XGM effect of the single SOA, the Q-factor of the proposed microwave band-pass filter was improved [9]. In the proposed microwave band-pass filter, so that the pole is closer to the unit circle, the gain of the recursive loop was optimized by using the EDFA and the VOA, and the wavelength conversion efficiency of the RSOA was optimized by controlling the injected current of the RSOA. The measured frequency response represented good correlation with the result obtained from the simulation. However, in Figure 5,

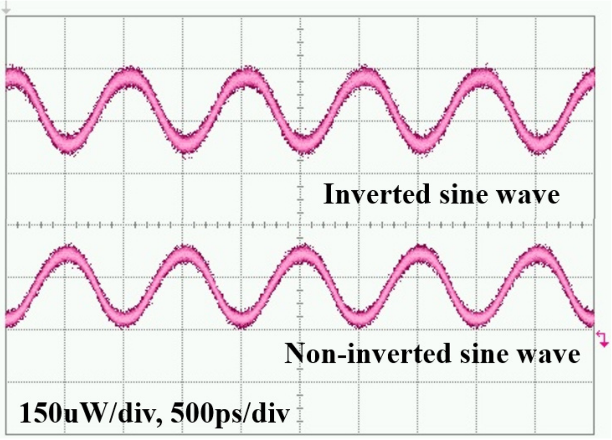

FIG. 4. Non-inverted and inverted sine waves measured at port 3 of the circulator.

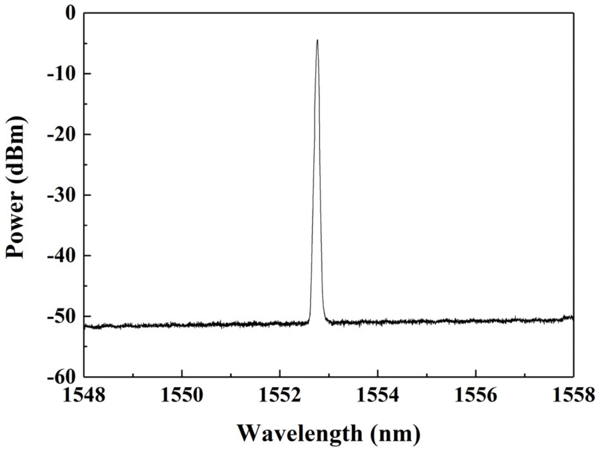

FIG. 3. Measured optical spectrum of the self-injection locked light generated by the RSOA.

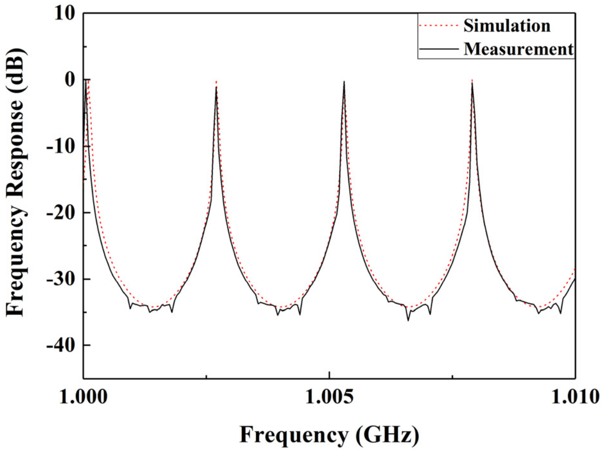

FIG. 5. Frequency responses of the proposed photonic microwave filter (Dashed: simulation. Solid: measurement).

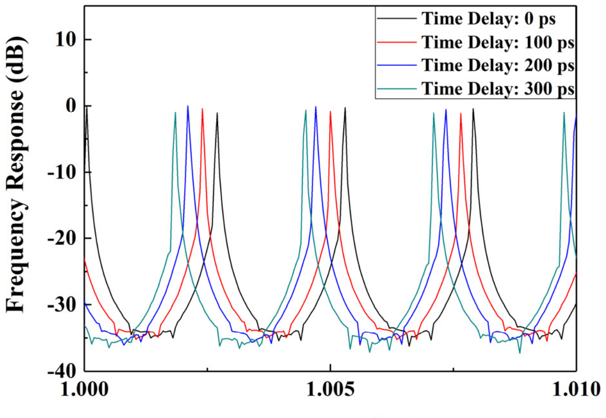

FIG. 6. Measured frequency responses of the proposed photonic microwave filter corresponding to the change of the time-delay using the optical time-delay line.

small dips between the peaks of the frequency response were observed because the residual reflection occurred due to the RSOA and the FBG #1. They induce parasitic delays caused by slight reflections, which reinject signals into the recursive loop. To reduce the small dips in the proposed filter, the RSOA with low-level facet reflectivity on one side should be chosen. In addition, the reflectivity of the FBG should be selected by considering the condition for the generation of the injection locked light and XGM effect, and the minimization of the residual reflection. Thus, the FBG with the reflectivity of about 35 % was chosen in the proposed filter.

Figure 6 shows the measured frequency responses of the proposed photonic microwave filter. The lines of different colors mean pass-band tunability by changing the optical time delay. As shown in the Eq. (3), as the time delay of the optical time-delay line was tuned from 0 to 300 ps, it was observed that the passband center frequency of the proposed filter was decreased by an amount of about 1 MHz in the figure.

IV. CONCLUSION

A simple tunable photonic microwave band-pass filter with high resolution using an RSOA was proposed and demonstrated. In the proposed filter, the RSOA was used as a gain medium for XGM effect as well as an optical source with narrow spectral width in conjunction with an external FBG. Furthermore, the controllability of the passband of the proposed filter was achieved by changing the time-delay of the recursive loop using an optical time-delay line. The proposed band-pass filter showed FSR of about 2.65 MHz, stopband rejection level of about 34 dB, and *Q*-factor of about 81. And, the tuning range of the passband center frequency was about 1 MHz in the proposed filter.

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