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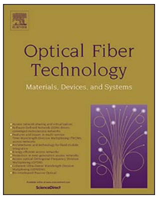

Regular Articles

Bandwidth tunable microwave photonic filter based on digital and analog modulation

Qi Zhang, Jie Zhang, Qiang Li, Yubing Wang, Xian Sun, Wei Dong*, Xindong Zhang

State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, 2699 Qianjin Street, Changchun 130012, China

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ABSTRACT

A bandwidth tunable microwave photonic filter based on digital and analog modulation is proposed and experimentally demonstrated. The digital modulation is used to broaden the effective gain spectrum and the analog modulation is to get optical lines. By changing the symbol rate of data pattern, the bandwidth is tunable from 50 MHz to 700 MHz. The interval of optical lines is set according to the bandwidth of gain spectrum which is related to the symbol rate. Several times of bandwidth increase are achieved compared to a single analog modulation and the selectivity of the response is increased by 3.7 dB compared to a single digital modulation.

1. Introduction

Microwave photonic filter (MPF) could provide benefits on microwave signal processing because of the photonic technique. It offers the advantages of low loss, large bandwidth, immunity to electromagnetic interference (EMI), reconfigurability and tunability [1–3]. Compared to copper cables, microwave photonic signals experience only very low propagation losses in optical fibers (~0.2 dB/km). Moreover, MPFs offer the ability to realize flexible tunability, reconfigurability and offer the potential for light-weight and small-footprint modules which are very difficult or even impossible to achieve with traditional technologies [4,5].

By now, several single passband MPFs have been proposed and successfully demonstrated based on a phase modulator (PM) and different optical filtering components [6–8]. Thanks to the inherent high Brillouin gain and its low threshold power, stimulated Brillouin scattering (SBS) based MPFs are capable of realizing broadened bandwidth and arbitrary shape of the response with high resolution [9–11]. The filter bandwidth can be broadened by using a pump light with flat multi-line spectra that are equally spaced up to or less than the natural Brillouin linewidth [12]. Several architectures have been demonstrated to construct multiple optical lines, such as multi-tone modulation [13], multi-sideband spectra generated by externally modulation [14–16], and fast frequency-sweeping pump [17,18]. However, the main drawback of this technique is the SBS intrinsic narrow bandwidth, typically several tens of megahertz (~30 MHz) [19], and this too-narrowband characteristic limited the bandwidth of the frequency response. If the linewidth of the pump wave is not negligible with respect to the Brillouin linewidth, the effective gain spectrum can be obtained by the convolution of the normalized spectrum of the laser with the inherent Brillouin gain spectrum of the fiber [20]. Some power spectrum broadening depends on direct modulation has been reported [21]. Direct modulation is low loss and cost-effective but suffers from poor tunability and stability since the laser is easily influenced by thermal effect. Compared with direct modulation, external modulation is more stable and convenient.

This paper combines the digital modulation and analog modulation to realize multiple optical lines with broadened effective gain spectrum. The laser power spectrum is effective broadened by applying a simple Binary Phase Shift Keying (BPSK) modulation. And the effective gain spectrum is the convolution of the normalized spectrum of the laser with the inherent Brillouin gain spectrum of the fiber. According to numerical simulation and experimental results, several times of bandwidth are increased compared to the case that is free from digital modulation [22]. The filter with single passband of 50–700 MHz bandwidth is demonstrated. The selectivity of the response is increased by 3.7 dB compared to the single digital modulation [23].

2. Principle of operation

Fig. 1 shows the experimental setup of the proposed MPF. A single tunable laser is used to generate both the pump and stokes wave. It is divided into two branches by a coupler. In the lower branch, the optical carrier is modulated by Mach-Zehnder modulator (MZM) with a serial of Pseudo Random Binary Sequence (PRBS) injected. The BPSK modulated signal functions as an optical carrier of second modulator. The frequency of the RF signal is set less than the linewidth of broadened effective gain spectrum. The half-wave voltage of the first MZM is 6.5 V

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* Corresponding author.
E-mail address: dongw@jlu.edu.cn (W. Dong).

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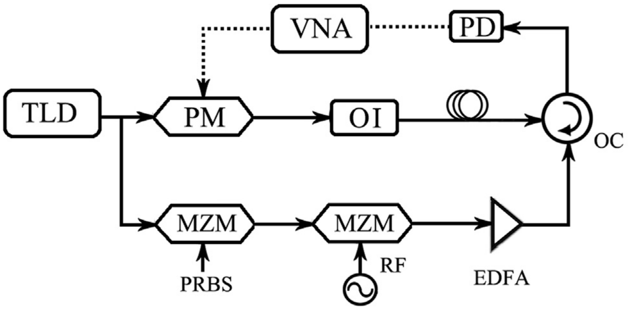

Fig. 1. Block diagram of the proposed filter. TLD: tunable laser diode; VNA: vector network analyzer; PM: phase modulator; OI: optical isolator; PRBS: Pseudo Random Binary Sequence; MZM: Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier; OC: optical circulator; PD: photodetector.

and the data rate is up to 10 Gbps. The electro-optical bandwidth of the second MZM is 10 GHz. After amplified by an erbium-doped fiber amplifier (EDFA), the modulated signal is sent into SBS effect including an optical circulator and 1 km long high nonlinear fiber (HNLF).

In the upper branch, the tunable laser is fed into a PM without basis voltage control. For small signal modulation, the two first-order sidebands of the phase modulated signal are out of phase. If the phase modulated signal is applied directly to the photodetector (PD), no signal would be detected except dc since the beating between the optical carrier and the upper sideband will cancel completely the beating between the optical carrier and the lower sideband due to the fact that the two beat signals are out of phase with a balanced intensity. However, when introducing the SBS process, the balance of intensity between two sidebands is broken, and then the corresponding RF signal can be detected by PD. A swept signal with bandwidth ranging from 40 MHz to 40 GHz, which covers the SBS gain region, is produced by a vector network analyzer (VNA), and then it modulates the light emitting from the tunable laser as a probe signal. The probe light propagates in fiber and is amplified once it is covered within the SBS gain region. The optical isolator (OI) is to prevent the residual pump power from the PM. The processed probe signal is detected by PD and the frequency response is measured by the VNA. The bandwidth of PD is 34 GHz and the responsivity is 0.85 A/W.

There are many optical digital modulation formats used for fiber-optic communication systems, such as Nonreturn-to-Zero On/Off Keying (NRZ-OOK), Carrier-Suppressed Return-to-Zero (CSRZ), BPSK, or Binary Differential Phase Shift Keying (DPSK). However, the NRZ-OOK and CSRZ optical spectrum are composed of a continuous portion and a strong discrete tone at the carrier wavelength. The strong discrete tone is the distortion to the effective gain spectrum if the NRZ-OOK or CSRZ modulation is adopted. Only the BPSK or DPSK optical spectrum which is composed of a continuous portion can be adopted to broaden the pump spectrum [24]. To perform optical phase modulation, one can either use a straight-line PM or an MZM. When using MZM, the modulator is driven around zero transmission [25], that the MZM bias is controlled at its transmission null point.

The power spectrum is broadened by BPSK modulation in which a binary phase modulation between 0 and π is applied to a signal. The modulation digital baseband signal is usually Nonreturn-to-Zero (NRZ). If the probability of the 0 and 1 is 1/2, that is P = 1/2, the power spectrum of the BPSK modulation signal depends entirely on the bit rate B of the PRBS.The effective gain spectrum $g(f)$ is the convolution of the intrinsic SBS gain function $g_i(f)$ and the power spectrum of the pump field $I_p(f)$, which is expressed as [20].

$$\begin{aligned} g(f) &= g_i(f) \otimes I_p(f) \\ &= \int_{-\infty}^{\infty} \frac{g_B I_P(f)}{1 - i(f + \nu_B - f_p)/(\Delta\nu_B/2)} df_P \end{aligned} \tag{1}$$

where $g_i(f) = g_B/[1-i(f+\nu_B-f_p)/(\Delta\nu_B/2)]$ is intrinsic SBS gain function, g_B is the linear gain coefficient and $\Delta\nu_B$ is the Brillouin intrinsic linewidth, ν_B is the brillouin frequency shift to pump.

The power spectrum of pump wave after BPSK modulation is given as:

$$I_p(f) = \frac{1}{B} \frac{\sin^2[\pi(f-f_0)/B]}{[\pi(f-f_0)/B]^2} \tag{2}$$

If the spectral width of the power spectrum is much wider than $\Delta\nu_B$, the real part of $g(f)$ may be approximated by $\mathrm{Re}[g(f)] \propto I_P(f+\nu_B)$ [21], and the corresponding effective gain spectrum is calculated in Fig. 2(a). The real part leads to an amplification of the counter propagating stokes wave, whereas the imaginary part results in an accompanied phase shift.

When the interval between the optical lines is set less than the bandwidth of effective gain spectrum, the multiple gain spectrum would overlap. After introducing SBS process, the incoming optical field before PD can be expressed as:

$$\begin{aligned} E(t) &= J_0(m)\exp(j2\pi f_c t) \\ &+ J_1(m) \times \exp\left\{j\left[2\pi(f_c + f_m)t + \frac{\pi}{2}\right]\right\} \times \prod_{k=1}^{N} G_k(f_m) \\ &- J_1(m) \times \exp\left\{j\left[2\pi(f_c - f_m)t - \frac{\pi}{2}\right]\right\} \end{aligned} \tag{3}$$

where $G_k(f_m)$ is relative to the SBS process:

$$\begin{aligned} G_k(f_m) &= \exp\{\mathrm{Re}[g(f_c + f_m)]\} \\ &= \exp\left\{\frac{L_{eff}}{A_{eff}} \frac{I_{pk}}{B} \frac{\sin^2[\pi(f_c + f_m - f_{pk} + \nu_B)/B]}{[\pi(f_c + f_m - f_{pk} + \nu_B)/B]^2}\right\} \end{aligned} \tag{4}$$

Omitting the dc and the small second harmonic components, the

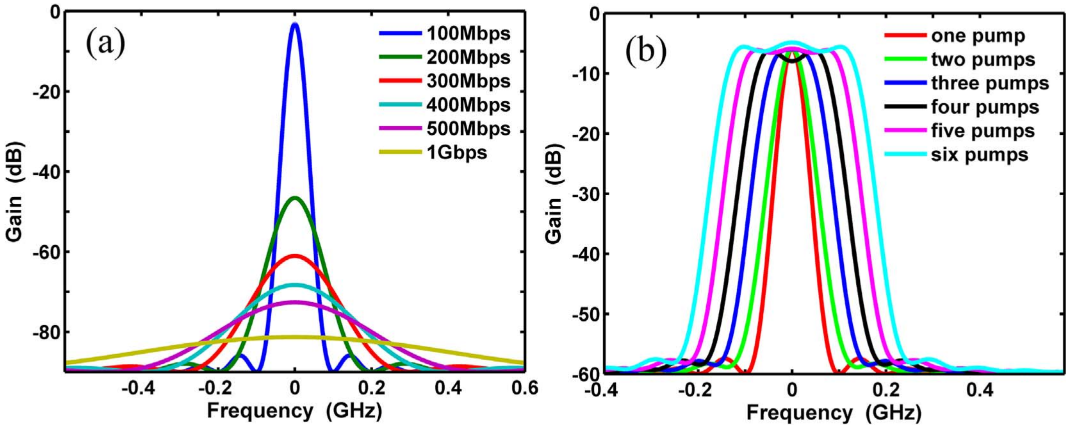

Fig. 2. Processed effective gain spectrum (a) and the broadened filter response when B = 100 Mbps (b).