Tunable Photonic Microwave Filter Using a Superstructured FBG With Two Reflection Bands Having Complementary Chirps

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***Abstract*—A tunable photonic microwave bandpass filter using a superstructured fiber Bragg grating (SFBG) with two reflection bands having complementary chirps is proposed. Being different from a regular chirped FBG, which is usually fabricated using a chirped phase mask with a fixed chirp rate, the SFBG with complementary chirps is fabricated using a uniform phase mask and a chirped sampling function. The chirp rate of the sampling function can be designed to realize specific equivalent chirp rates that are complementary in the $+1$st-order and the -1st-order reflection bands of the SFBG. An SFBG with complementary chirps is fabricated and characterized. The use of the SFBG to implement a photonic tunable microwave filter with a negative coefficient is experimentally demonstrated.**

***Index Terms*—Equivalent chirp, photonic microwave filter, superstructured fiber Bragg grating (SFBG), tunable microwave filter.**

I. INTRODUCTION

ALL-OPTICAL microwave filters have been a subject of active research in the past few years [1]–[9]. Compared with their electrical counterparts, photonic microwave filters provide advantages such as low loss, light weight, broad bandwidth, immunity to electromagnetic interference (EMI), and, very importantly, large tunability, which is often hard to achieve with electrical methods. To avoid optical interference, photonic microwave filters are usually designed to operate in the incoherent regime. An incoherent photonic microwave filter can usually provide all positive coefficients. It is known that a microwave delay-line filter with all positive coefficients can only function as a low-pass filter, or a special design should be incorporated to generate negative coefficients with bandpass functionality [1]–[9]. In this letter, we demonstrate a two-tap all-optical microwave filter with one negative coefficient based on optical phase-modulation-to-intensity-modulation (PM-IM) conversion in a superstructured fiber Bragg grating (SFBG) with two reflection bands having complementary chirps. The key component in the filter is the chirped SFBG, which is fabricated using a uniform phase mask by applying an equivalent chirp to the sampling function. The PM-IM conversion, which is realized in the $+1$st-order and the -1st-order reflection bands of the SFBG, generates positive and negative coefficients. An SFBG is fabricated and its application in a photonic microwave bandpass filter is demonstrated.

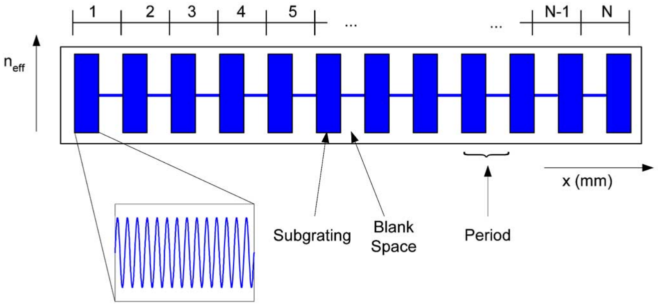

Fig. 1. Refractive index profile of an SFBG.

II. SFBG WITH COMPLEMENTARY CHIRP RATES

An SFBG, also called sampled FBG, is a combination of subgratings and blank spaces. A subgrating is a short FBG inside the superstructure and a blank space is an area where the ac variation of the refractive index is null, but where the dc component is often increased to reach a constant value throughout the superstructure. Fig. 1 shows a possible refractive index profile of an SFBG. Analogous to Fourier theory, uniform sampling of an FBG in the spatial domain will lead to a periodic spectrum. By adjusting the spatial sampling function, it has been demonstrated that various spectrum profiles can be achieved [10]–[12].

SFBGs offer key advantages in many applications mainly because of the flexibility they offer. By adjusting the parameters of the sampling function, it is possible to achieve different reflection and transmission spectra as well as different dispersion profiles with a single uniform phase mask.

As shown in Fig. 1, the SFBG is composed of N sections, with each section consisting of a subgrating and a blank space. The length of a section is referred to as the sampling period Z and the length of a subgrating is defined as Ls. It has been demonstrated that by chirping the sampling period along the length of the SFBG, it is possible to achieve an equivalent chirp in the Fourier orders of the SFBG spectrum [11]. We express the sampling period as a function of the physical position along the grating length x as follows:

$$Z(x) = Z_0(1 + \zeta_1 x + \zeta_2 x^2) \qquad (1)$$

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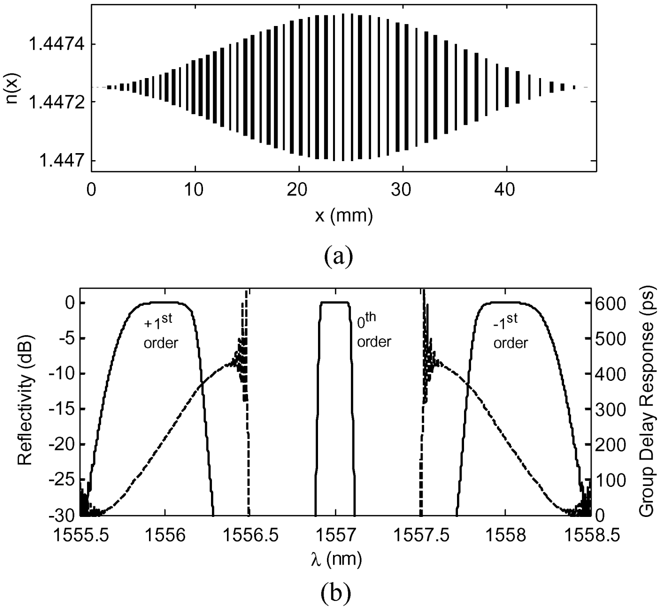


(a)

(b)

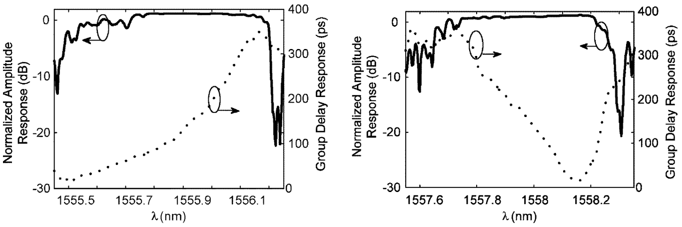
Fig. 2. Refractive index profile of a sine-square apodized SFBG with equivalent chirp in its sampling profile. The parameters of the superstructure are as follows: $Z_0 = 0.56$ mm, $Ls = 0.28$ mm, $N = 60, \zeta_1 = 0.021103, \zeta_2 = 0$. (b) Simulated spectrum (solid line) and group delay response in the $+1$st and -1st orders (dashed line) of the SFBG.

where Z_0 is the initial sampling period and ζ_1 and ζ_2 are the linear and nonlinear chirp coefficients, respectively. Fig. 2(a) shows the refractive index profile of an SFBG. In order to eliminate the strong sidelobes present in the amplitude spectrum and the important group delay ripple, an apodization profile can be used. A sine-square apodization profile of the superstructure is also shown in Fig. 2(a). Fig. 2(b) shows the simulated spectrum and the group delay response of an apodized SFBG with equivalent chirp. As can be seen, the two 1st orders have similar amplitude responses, but with complementary group delay responses.

An SFBG is fabricated on hydrogen loaded fiber with the following superstructure parameters: $Z_0 = 0.56$ mm, $Ls = 0.28$ mm, $N = 60$, $\zeta_1 = 0.021103$, and $\zeta_2 = 0$. The reflection spectrum of the fabricated SFBG and its group delay response are shown in Fig. 3. Fig. 3(a) shows the responses of the $+1$st order while Fig. 3(b) shows the response of the -1st order. As it can be seen, the spectra at both reflection bands are similar, but with complementary group delay responses. Ripples are observed in the passbands of the ± 1st orders of the fabricated SFBG, and they are attributable to errors associated with the fabrication process. The $+1$st and -1st orders have a usable 3-dB bandwidth of 0.67 and 0.61 nm and an average dispersion within the 3-dB bandwidth of about $\chi = 550$ ps/nm and $\chi = -825$ ps/nm, respectively. The discrepancies in the group delay responses between the two bands are due to fabrication errors.

III. ALL-OPTICAL MICROWAVE TUNABLE BANDPASS FILTER

The fabricated SFBG is then incorporated in an all-optical tunable microwave bandpass filter, as shown in Fig. 4. Instead of using an intensity modulator, the proposed filter configuration uses an electrooptic phase modulator (EOPM). We have recently demonstrated that a photonic microwave filter using an EOPM can generate negative coefficients when PM-IM conversion is implemented by dispersive devices with complementary dispersions [8], [9].



(a)

(b)

Fig. 3. Measured reflection spectrum and group delay response of the (a) $+1$ order and (b) -1 order of the realized equivalent-chirp SFBG.

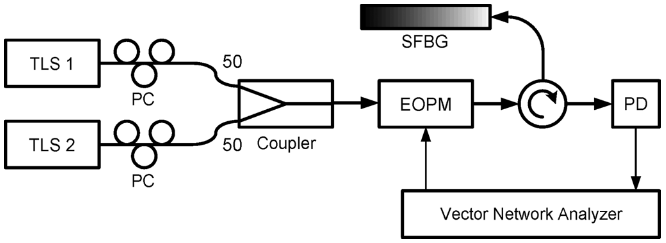


Fig. 4. Experimental setup of the proposed all-optical microwave filter based on an SFBG. PC: polarization controller; Coupler: 50/50 optical coupler; PD: photodetector.

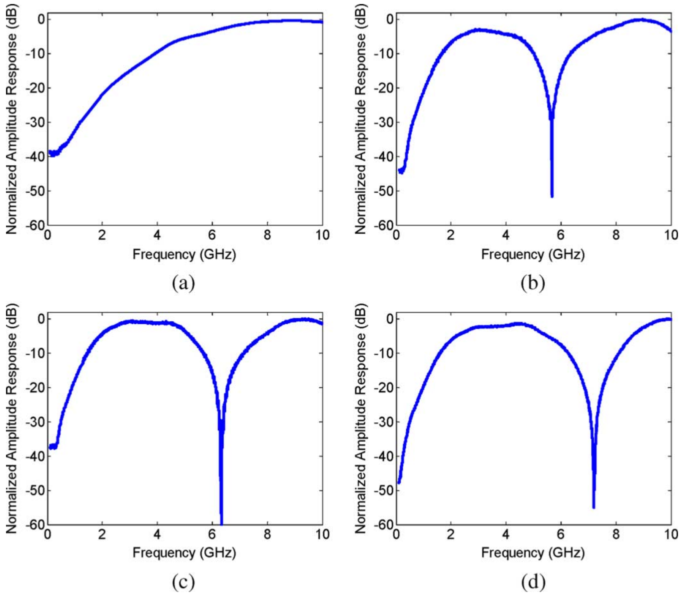
Mathematically, the transfer function of the proposed filter configuration is given by

$$H(\omega) \propto \sum_{n=1}^{2} P_n \sin\left(\frac{D_n \Omega^2}{2}\right) e^{j\Omega(n-1)\Delta\tau} \tag{2}$$

where P_n is the optical power of the nth tap before the PD, D_n is the dispersion of the nth tap, Ω is the RF signal frequency, and $\Delta\tau$ is the time delay difference between the two taps, resulted from the different reflection locations at the SFBG.

This configuration can be extended to a bandpass filter with multiple taps, by adding more light sources. The wavelengths of these light sources must be located in either the $+1$st-order or -1st-order band to generate positive or negative coefficients.

The setup shown in Fig. 4 is experimentally demonstrated. An RF signal generated by a vector network analyzer (Agilent E83648) is applied to the EOPM to phase-modulate two optical carriers from two tunable laser sources (TLSs) that are combined via a 50/50 optical coupler. The wavelength of one TLS is chosen to be within the 3-dB bandwidth of the $+1$st order while the wavelength of the other TLS is within the 3-dB bandwidth of the -1st order of the SFBG. The phase-modulated optical signals are sent to the SFBG through an optical circulator. The two phase-modulated signals are converted to intensity-modulated signals at the SFBG. Because of the complementary nature of the dispersions in the $+1$st and -1st orders, the converted intensity-modulated signals are out of phase, which are detected at a photodetector. A microwave filter with one negative and one positive coefficient is thus achieved.



(a) (b) (c) (d)

Fig. 5. (a) Experimental frequency response of the PM-IM conversion using an equivalent-chirp SFBG with dispersion values of $\chi = -825$ ps/nm in the -1st order; frequency response of the all-optical tunable microwave filter when the time difference between the two optical signals is equal to (b) 180, (c) 160, and (d) 140 ps.

IV. EXPERIMENTAL RESULTS

We first demonstrate the PM-IM conversion using the SFBG. In this case, only one TLS is used with its wavelength tuned to locate in one of the two reflection bands. As shown in Fig. 5(a), a transfer function which corresponds to the PM-IM conversion is obtained. The dispersion of the SFBG in the -1st order is about $\chi = -825$ ps/nm, which gives the first peak at 8.70 GHz. This theoretical value matches well with the experimental result shown in Fig. 5(a). When the two TLSs are used with their wavelengths tuned within the two reflection bands, the system becomes a microwave filter with two taps. The time delay difference between the two taps is determined by the group delay difference. By tuning the wavelength of one of the TLS, the refection location at the SFBG will be changed, leading to a change to the time-delay difference. A tunable free spectral range (FSR) of the filter is thus realized. The measured frequency responses of the microwave filter with the different time delay differences of 180, 160 and 140 ps are shown in Fig. 5(b), (c) and (d), corresponding to an FSR of about 5.5, 6.25, and 7.25 GHz, respectively. As it can be seen, the microwave filter responses match the FSR values calculated based on the time delay differences. A minimum FSR of 2.86 GHz is obtained when the time delay difference is equal to 350 ps. This time delay difference is limited by the dispersion values of the ± 1st orders of the SFBG and their usable bandwidth.

V. CONCLUSION

A photonic microwave bandpass filter with a negative coefficient using an SFBG with two reflection bands having complementary dispersions was proposed and experimentally demonstrated. Both a negative and a positive coefficient were generated based on PM-IM conversion in the $+1$st and -1st orders of the SFBG. The tunability of the filter was realized by tuning the wavelength of one of the TLSs. The microwave filter demonstrated here can be extended to a multitap microwave bandpass filter by adding more light sources, of which the wavelengths must be located in either the $+1$st-order or -1st-order band to generate positive or negative coefficients. The stability of the filter depends mainly on the stability of the SFBG, which can be improved by proper packaging and temperature control. The key advantage of using an SFBG with equivalent chirp rates is that a single uniform phase mask is needed to generate gratings with different equivalent chirps. In addition, the complementary nature of the dispersions in the -1st- and $+1$st-order reflection bands allow a single SFBG to generate both positive and negative coefficients.

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