Ultrawide Tunable Microwave Photonic Notch Filter Based on Stimulated Brillouin Scattering
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Abstract—A new ultrawide tunable microwave photonic notch filter that exhibits a very high resolution is presented. It is based on a stimulated Brillouin scattering technique, which processes the modulation sidebands generated by a dual-drive Mach–Zehnder modulator. Tuning is realized by changing the drive frequency to an electro-optic intensity modulator. Experimental results demonstrate a high-resolution notch filter with a 3-dB bandwidth of 82 MHz, a notch depth of over 40 dB, a flat passband from near DC to 20 GHz with very low ripples, and a notch frequency that can be continuously tuned with shape invariance over an ultrawide frequency range from 2 to 20 GHz.

Index Terms—Microwave filters, microwave photonics, notch filters, stimulated Brillouin scattering (SBS).

I. INTRODUCTION

PHOTONIC approaches for the processing of microwave and radio frequency (RF) signals have attracted significant interest because they have advantages of high bandwidth capability, wide tuning potential, and electromagnetic interference (EMI) immunity [1]. The implementation of microwave photonic notch filters is of particular interest for interference rejection functions in applications such as fiber-fed antenna arrays and radar, where it is important to eliminate the unwanted high-amplitude interfering signals that the antenna picks up in addition to the desired signal, to avoid undue demands on the dynamic range requirements.

A range of structures for microwave photonic notch filters have been reported [2]–[6]. However, structures based on the FIR approach [2], [3] have been limited to synthesizing only a small number of taps, e.g., a two-tap filter can achieve a deep notch filter, however because it exhibits a very gradual frequency response it also degrades the wanted passband, which is undesirable. Structures based on the IIR [4], [5] approach can realize high-resolution narrow notch operation, however they have been limited by their small free spectral range (FSR), which is constrained by the length of the cavity. Recently, an improved microwave photonic notch filter based on silicon ring resonators has been reported [6], which can be tuned from 2–15 GHz, however the notch 3-dB bandwidth of 910 MHz was quite wide and since tuning was via thermo-optic heaters, critical temperature control is required for accurately aligning the dual notch optical filters to the RF aligning optical filters to the modulation sidebands. Stimulated Brillouin scattering (SBS) is attractive for realizing narrowband filters, and we have recently reported a structure using a phase modulator for implementing a bandpass filter [7], however it is not possible for this phase modulator structure to realize a notch filter.

This letter reports a new structure which enables a notch filter with high-resolution to be achieved. The concept is based on introducing a device that can produce out-of-phase asymmetrical-amplitude optical modulation sidebands, namely a dual-drive Mach–Zehnder modulator (DDMZM), in conjunction with a design for the phase bias of the DDMZM that produces this modulation. Using SBS to process the generated sidebands from the DDMZM, experimental results for the new structure are presented which demonstrate the realization of a notch filter with wide tunability, high resolution, large notch depth, flat passbands, and shape-invariant continuous notch tuning.

II. OPERATIONAL PRINCIPLE

The structure and operational principle of the new microwave photonic notch filter is shown in Fig. 1. Light from the laser diode (LD) is split and routed into two paths. The upper branch contains the DDMZM which is driven by the input RF signal \( f_{RF} \) through a 3 dB quadrature hybrid coupler. This is followed by a length of fiber where the SBS process occurs. The lower branch contains an electro-optic intensity modulator (IM) which is driven by the pump signal \( f_p \) to produce a double-sideband carrier-suppressed signal as the pump wave for the SBS process. This pump signal is injected into the fiber in the counter-propagating direction to the RF modulated signal by means of an optical circulator. Fig. 1 also shows the optical spectra after the key points in the system. For small signal modulation, the optical field of the RF modulated signal after the DDMZM can be described as

\[
E(t) = \frac{E_0}{2} \left[ (e^{j\theta} + 1)J_0(m)e^{j2\pi f_c t} + (e^{j\theta} + j) \times J_1(m)e^{j2\pi (f_c + f_{RF})t} - (e^{j\theta} - j) \times J_1(m)e^{j2\pi (f_c - f_{RF})t} \right]
\]

(1)

where \( E_0 \), \( f_c \), is the amplitude and frequency of the laser after the coupler, \( V_{RF}, f_{RF} \) is the amplitude and frequency of the input RF signal, \( V_a \) represents the half-wave voltage and \( \theta = \pi \sqrt{\frac{P_{DC}}{N_C}} \) is the phase induced by the DC bias, \( m = \pi V_{RF}/(\sqrt{2}V_a) \) is the RF signal induced phase, and \( J_n(\cdot) \) denotes the \( n^{th} \)-order Bessel function of the first kind with \( n = 0, \pm 1 \). It should be noted that the amplitudes and phases...
After the PD can be expressed as because the beating is out of phase. This produces a narrow sideband amplitudes as shown in spectrum (ii) of Fig. 1, hence there is no RF signal produced at the photodetector output sideband amplitudes in the upper branch of Fig. 1. Under these conditions, the output field of the RF modulated signal can be simplified to

\[
E(t) = a_0 e^{j2\pi f_p t + \phi} + b_0 e^{j2\pi (f_c + f_{RF}) t + \phi + \frac{\pi}{4}} + c_0 e^{j2\pi (f_c - f_{RF}) t + \phi + \frac{3\pi}{4}}
\]

(2)

where \( \phi \) is the phase of the carrier, \( a = E_0 \cos(\pi + \theta/2) \) \( J_0(m)/2 \) (a > 0) is the amplitude of the carrier, and \( b = E_0 \sin(\pi/4 - \theta/2) J_1(m)/2 \) and \( c = E_0 \sin(\pi/4 - \theta/2) J_0(m)/2 \) denote the amplitudes of the upper sideband and lower sidebands respectively with \( c > b > 0 \).

We consider the case where the pump frequency \( f_p \) is greater than the Brillouin frequency shift \( f_B \), i.e., \( f_p > f_B \). If \( f_{RF} \) is at a frequency where the sidebands of the RF modulated signal do not fall on the SBS gain or loss frequency induced by the pump wave, as shown in spectrum (i) of Fig. 1, then there is no effect on the RF modulated signal and an RF signal is produced at the photodetector (PD) output since the lower sideband amplitude is high while the upper sideband amplitude is negligible. However, when \( f_{RF} = f_p - f_B \) the upper sideband is amplified while the lower sideband is attenuated. For a given pump power and SBS gain, the DC voltage bias of the DDMZM is chosen to equalize the two sideband amplitudes as shown in spectrum (ii) of Fig. 1, hence there is no RF signal produced at the photodetector output because the beating is out of phase. This produces a narrow notch response. Following the SBS effect, the output RF power after the PD can be expressed as

\[
P(f_{RF}) \propto 2a^2 R^2 \left| b \cdot |G(f_c + f_{RF})| - c \cdot |G(f_c - f_{RF})| \right|^2
\]

(3)

where \( R \) is the PD responsivity, \( R \) is the load resistance and \( G \) denotes the SBS amplitude gain/loss. For a given SBS gain and loss, the required phase bias \( \theta \) on the DDMZM to produce a notch can be derived from (3) as

\[
\theta = \frac{5}{2} \pi - 2 \tan^{-1} \left( \frac{G(f_c + f_p - f_B)}{G(f_c - f_p + f_B)} \right).
\]

(4)

Since the notch frequency is at \( f_p - f_B \), it can readily be tuned by simply changing drive frequency \( f_p \) to the IM in Fig. 1. This technique is effective in providing tunable high-resolution notch filtering for arbitrary RF input signal spectra.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Experiments were set up to verify the proof of principle for the new microwave photonic notch filter structure. The experimental setup is shown in Fig. 2. Light from a LD operating at 1550 nm and with an output of 10 dBm, was split using a 3 dB coupler. The upper arm comprised a DDMZM driven through a 4–44 GHz 3 dB quadrature hybrid coupler by the input RF signal, which was the output of a vector network analyzer (VNA). The half-wave voltage of the DDMZM \( V_x \) was around 5.212 V. The DC bias of the DDMZM could be changed from 0 to 11 V by means of a power supply. After amplification by an erbium-doped fiber amplifier (EDFA1), the RF modulated signal was launched into a 1 km length of dispersion shifted fiber (DSF) that had a dispersion value of 0.0 ± 1.0 ps/nm-km and an effective area of around 11.7 \( \mu \text{m}^2 \); the latter increased the Brillouin gain coefficient because of its small core value. The Brillouin frequency of the DSF was 9.21 GHz.

The lower branch comprised an IM, which was biased at the minimum transmission point to generate the double-sideband suppressed-carrier modulated pump signal. It was driven by an RF generator having frequency \( f_p \), which was continuously tunable from 11.21 GHz to 29.21 GHz. After amplification by EDFA2, the pump signal was injected into the DSF through a 4–44 GHz 3 dB circulator in the counter-propagating direction to the RF modulated signal in the upper branch. The isolator (ISO) was used to eliminate the pump wave after it passed through the DSF.

The SBS process occurred in the DSF between the RF modulated signal and double-sideband pump signal. Since the DDMZM, the IM, and the SBS effect are polarization dependent, polarization controllers PC1, PC2, PC3 and PC4 were used to align the polarization as shown in Fig. 2; however these can be eliminated if polarization maintaining components are used. After the DSF, the optical signal was detected by a PD. The frequency response of the notch filter was measured using a VNA, which had a maximum sweeping frequency of 20 GHz.
A new structure for an ultra-wide tunable microwave photonic notch filter that exhibits extremely high resolution, high notch depth, flat passbands, and shape-invariant continuous notch tuning, has been presented. This can simultaneously excise interference with minimal impact on the wanted signal over a wide microwave range. It is based on an SBS technique. Tuning is simply realized by changing the pump signal frequency. Experimental results demonstrate a high-resolution notch filter with a 3-dB bandwidth of 82 MHz, a notch depth of over 40 dB, a flat passband from near DC to 20 GHz with very low ripples, and a notch frequency that can be continuously tuned with shape-invariance over an ultra-wide frequency range from 2 GHz to 20 GHz. To our knowledge, this is the widest continuously tunable frequency range reported to date, for a narrowband notch filter.

### IV. Conclusion

A new structure for an ultra-wide tunable microwave photonic notch filter that exhibits extremely high resolution, high notch depth, flat passbands, and shape-invariant continuous notch tuning, has been presented. This can simultaneously excise interference with minimal impact on the wanted signal over a wide microwave range. It is based on an SBS technique. Tuning is simply realized by changing the pump signal frequency. Experimental results demonstrate a high-resolution notch filter with a 3-dB bandwidth of 82 MHz, a notch depth of over 40 dB, a flat passband from near DC to 20 GHz with very low ripples, and a notch frequency that can be continuously tuned with shape-invariance over an ultra-wide frequency range from 2 GHz to 20 GHz. To our knowledge, this is the widest continuously tunable frequency range reported to date, for a narrowband notch filter.

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### REFERENCES


