High-Resolution Microwave Photonic Notch Filter with Low-Noise and Low Group Delay Ripple Performance

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Abstract

A high-resolution microwave photonic notch filter having a wide passband and a narrow notch, is presented. It is based on a WDM multiple double-pass modulation approach using Bragg grating reflectors. The WDM laser powers are optimised to flatten the filter passband and to improve the filter group delay performance. The filter operates over a wide frequency range, and the notch frequency is tunable. Experimental results demonstrate a microwave photonic notch filter with a wide and flat passband, a narrow notch at GHz frequency and a high signal-to-noise ratio performance. Tunable coherence-free operation of the notch filter is also shown.

1. Introduction

Microwave photonic systems for the distribution of signals have been the subject of significant interest. Photonic signal processing is attractive for providing EMI immunity and for its ability of realising in-built signal conditioning [1]. A range of microwave photonic notch filter structures has been reported [2-4]. However, they have either been limited to only generating a low-resolution two-tap notch filter response that is much too gradual and compromises the passband, or have generated excessive noise which limits the signal-to-noise ratio (SNR). Moreover, because of the additional difficulty in tuning, there have been very few reports of tuneable, multiple-tap photonic notch filters, that also have low noise. This paper presents a new microwave photonic notch filter structure that can realise a narrow high-resolution notch, which is tuneable, which has low-noise and low group delay ripple performance in the passband, and which is free of coherent interference limitations.

2. Microwave Photonic Notch Filter Topology

Fig. 1(a) shows the topology of the multiple double-pass modulation based microwave photonic notch filter. Continuous wave light from different-wavelength laser sources are combined via an N×1 coupler to form a WDM source, and is then modulated in the forward direction using an optical intensity modulator. A series of fibre Bragg gratings at wavelengths that match the laser wavelengths and at specific designed physical locations is connected to the modulator output, and reflect the modulated optical signals back into modulator to generate double-pass modulation in the reverse direction. The optical intensity modulator is an electro-absorption modulator (EAM), which operates bidirectionally. Finally, the optical signals are summed at the photodetector.

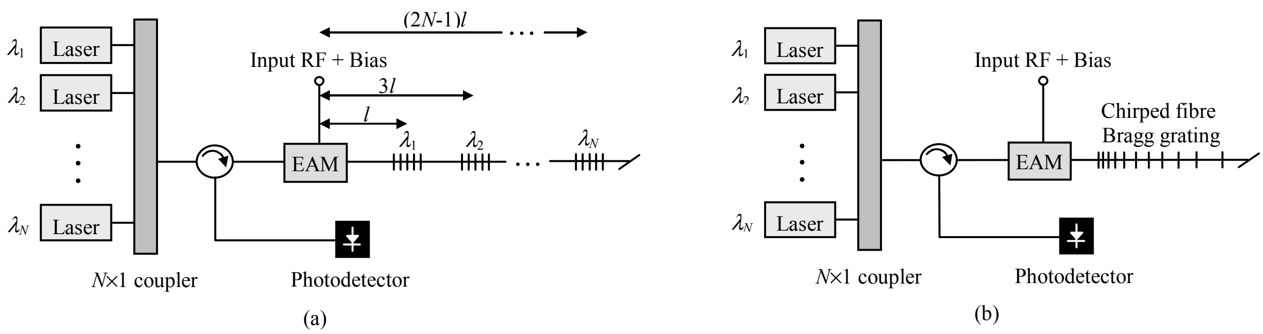

Fig. 1. Topology of the (a) fixed and (b) tuneable multiple double-pass modulation based microwave photonic notch filter.

For each wavelength, the second modulation in the double-pass process produces notches at all frequencies where the remodulation is an odd integer multiple of 180° phase difference to the returned modulated RF signal [5]. Thus each wavelength corresponding to a laser-grating pair in Fig. 1(a) produces an equivalent two-tap notch filter

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response with a free spectral range (FSR) that depends on the modulator to grating spacing. Our idea is to design the modulator-grating separations to be an odd integer multiple of the smallest modulator-grating separation. This ensures that all the notches originating from the different wavelengths are coincident at the desired frequency. After combining these responses, the passband is flattened and widened, and the desired notch is narrowed due to the superposition of the responses. This results in a notch filter response with a wide passband and a narrow notch. Since the modulator-grating separations control the notch frequency of the multiple double-pass modulation based microwave photonic notch filter, a continuously tuneable notch filter can be realised by simply replacing the grating array in the structure with a chirped fibre Bragg grating as shown in Fig. 1(b) and by tuning the laser wavelengths.

3. Analysis and Simulation Results

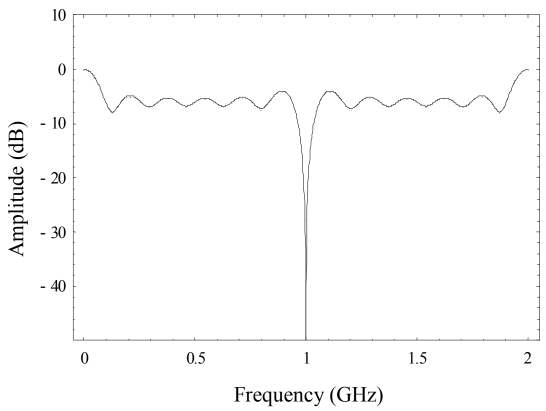
The multiple double-pass modulation based microwave photonic notch filter transfer function is given by

$$H(f) = \Re^2 R_{in} R_o \left\{ \left[X_{\lambda_1}(\cos\phi_1 + 1) + X_{\lambda_2}(\cos\phi_2 + 1) + ... + X_{\lambda_N}(\cos\phi_N + 1) \right]^2 + \left[X_{\lambda_1}\sin\phi_1 + X_{\lambda_2}\sin\phi_2 + ... + X_{\lambda_N}\sin\phi_N \right]^2 \right\} \tag{1}$$

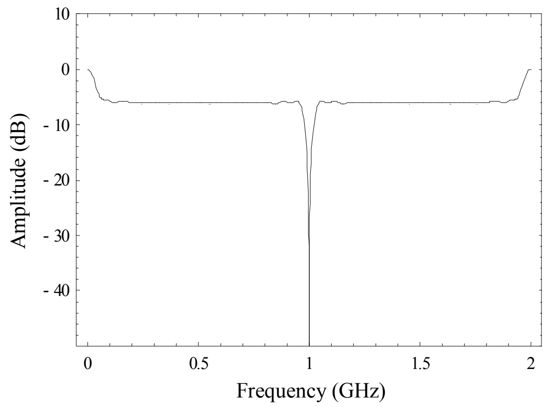
where $\Re$ is the photodiode responsivity, R_{in} is the modulator input resistance, R_o is the photodetector load resistance, $\phi_N = 2\pi f \cdot \tau_N$, τ_N is the round trip time which depends on the distance between the modulator and the N^{th} grating reflector, X_{λ_N} is the amplitude of the output signal at the λ_N wavelength, which is given by

$$X_{\lambda_N} = t_{ff,\lambda_N}{}^2 P_{i,\lambda_N} a_{0,\lambda_N} a_{1,\lambda_N} R_{\lambda_N} \tag{2}$$

t_{ff,λ_N} is the EAM insertion loss, P_{i,λ_N} is the EAM input optical power, a_{i,λ_N} is the i^{th} order Taylor's series coefficient of the transfer characteristic of the EAM operated at the wavelength λ_N, which is dependent on the modulator bias voltage, and R_{λ_N} is the N^{th} grating reflectivity.



(a)



(b)

Fig. 2. Frequency responses of the (a) six-wavelength double-pass modulation based microwave photonic notch filter and (b) sixteen-wavelength double-pass modulation based microwave photonic notch filter with optimised output signal amplitudes to minimise the passband ripple.

As an example, Fig. 2(a) shows the frequency response of a six-wavelength double-pass modulation based microwave photonic notch filter, using equal amplitude output signal at the different wavelengths and with the distances between the modulator and the six different wavelength gratings designed to be 5 cm, 15 cm, 25 cm, 35 cm, 45 cm and 55 cm respectively. Hence, the notch frequency is at 1 GHz. Fig. 2(a) shows a wide filter passband and a notch 3-dB bandwidth of 4% of the filter FSR. The notch narrowness can be improved by increasing the number of laser-grating pairs, e.g. increasing the laser-grating pairs from six to sixteen can narrow the notch 3-dB bandwidth from 4% to 1.5% of the filter FSR. Also, and importantly, the notch filter passband ripple can be reduced by designing the laser powers or the grating reflectivities to have a decreasing taper. A good empirical design guide was found to be one where the normalised amplitudes of the output signal at the λ_N wavelength are given by

$$X_{\lambda_N} = \frac{M - (N - 1)}{M} \tag{3}$$

where M is the total number of laser-grating pairs, which are used as very good initial values for optimisation. The optimum normalised output signal amplitudes for the sixteen different wavelength signals are 1, 0.94, 0.87, 0.8, 0.75, 0.68, 0.62, 0.5, 0.4, 0.35, 0.3, 0.25, 0.2, 0.15, 0.1 and 0.05. Fig. 2(b) shows the frequency response of the sixteen-wavelength double-pass modulation based microwave photonic notch filter with optimised output signal amplitudes. This shows that the passband ripple amplitude is significantly reduced to less than 0.5 dB over 90% of the filter FSR.

The corresponding notch filter impulse response is shown in Fig. 3(a). It can be seen that the output signal amplitudes decrease continuously. Note that the separation between the first two taps is τ=0.5 ns whereas the separations between all subsequent taps are 2τ=1 ns. This difference in tap separations leads to a nonlinear phase response, which causes the frequency components in the signal to be delayed by different amounts, thus resulting in ripples in the group delay response. Group delay ripples are undesirable as they cause signal distortion. However, until now, very little attention has been paid to minimising the group delay ripples of microwave photonic filters. We have found that the multiple double-pass modulation based microwave photonic notch filter group delay ripple can be reduced by optimising the output signal amplitudes. Fig. 3(b) shows the group delay response of the sixteen-wavelength double-pass modulation based microwave photonic notch filter with equal amplitude output signal at the different wavelengths. The filter fundamental notch frequency is 1 GHz. Fig. 3(c) shows the group delay response of the same filter after optimising the output signal amplitudes to be the same as the optimised values subsequent to (3) that were used to minimise the amplitude ripple in the passband. Comparison of Fig. 3(b) and 3(c) shows that the group delay ripple has been reduced by a factor of 10, ie. from 2 ns to 0.2 ns within the filter passband by optimising the output signal amplitudes. For reference, it has been shown that a filter having a group delay ripple of <1 ns enables communication without signal phase distortion [6]. Since the group delay ripple is inversely proportional to the filter FSR, this ripple value further reduces as the FSR is increased.

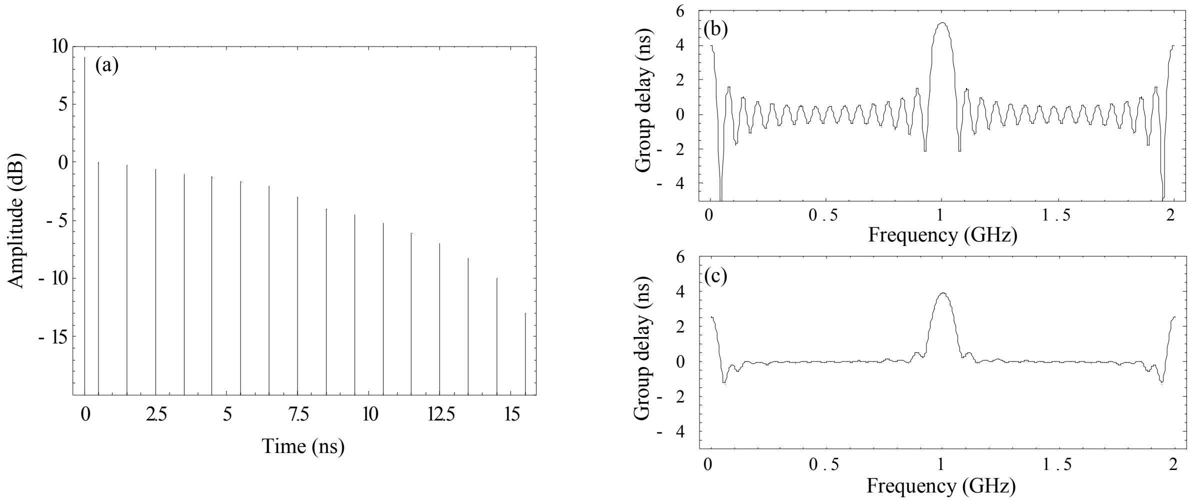
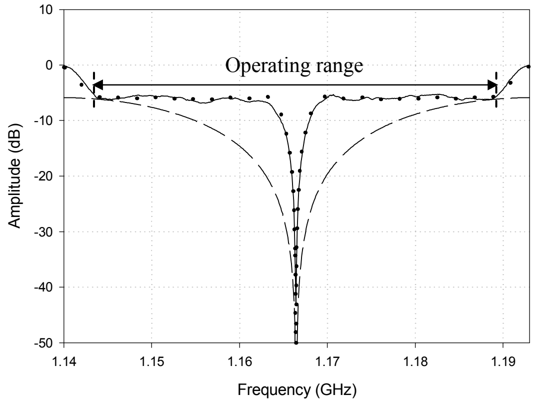


Fig. 3. (a) Impulse response of the sixteen-wavelength double-pass modulation based microwave photonic notch filter with optimised output signal amplitudes. Group delay response of the sixteen-wavelength double-pass modulation based microwave photonic notch filter (b) without and (c) with optimised output signal amplitudes.

4. Experimental Results

Experiments were set up based on Fig. 1(a) to verify of principle for the new microwave photonic notch filter topology. Six CW lasers were combined to form the WDM optical source. Since an EAM was unavailable, a wideband quadrature biased electro-optic modulator (EOM) was used instead. Six fibre Bragg gratings having >99% reflectivity and having the same wavelengths as the lasers were connected to the modulator output. The WDM double-pass modulated optical signals were passed through an optical circulator to a photodetector. The WDM laser powers were optimised so that the ratios of the N^{th} to 1^{st} laser-grating pair notch filter passband amplitude were 1, 0.85, 0.7, 0.45, 0.3 and 0.15, to reduce the filter passband ripples. Fig. 4(a) shows a comparison between the measured and predicted frequency responses of the six-wavelength double-pass modulation based notch filter with optimum designed output signal amplitudes. The frequency response of the conventional microwave photonic notch filter based on the Mach-Zehnder interferometer (MZI) structure is also shown in Fig. 4(a) as a reference, for comparison. This shows that the six-wavelength double-pass modulation based notch filter has a much narrower notch of 4% of the filter FSR compared to 50% in the case of the MZI based notch filter. The amplitude of the ripple in the six-wavelength double-pass modulation based notch filter passband was around 1 dB over the operating range which was 84% of the filter FSR. Due to the lack of a long chirped fibre Bragg grating, the tuneability of the multiple double-pass modulation based notch filter was demonstrated by using three tuneable laser sources and two sets of three different wavelength gratings. Fig. 4(b) shows the tuneable notch filter responses, which were obtained by adjusting the laser wavelengths to match the grating reflector wavelengths. The SNR of the multiple double-pass modulation based notch filter was measured by applying a microwave signal at the notch filter passband frequency to the modulator. An erbium-doped fibre amplifier was used after the circulator to compensate for the system loss and the optical power into the photodetector was -2.8 dBm. The notch filter SNR was measured on an electrical spectrum analyser and was found to be 119.5 dB/Hz. This high SNR demonstrates that the multiple double-pass modulation based notch filter has a low-noise performance.



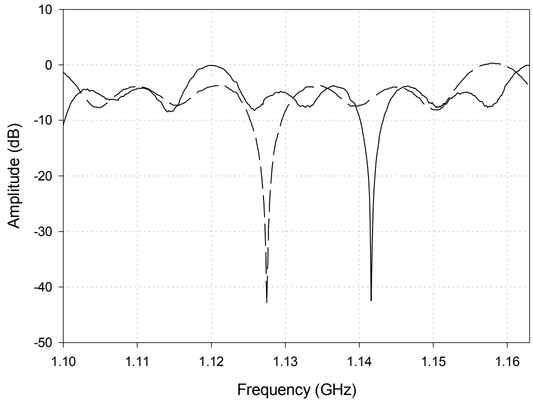


Fig. 4. (a) Measured (solid) and simulated (dots) responses of the six-wavelength double-pass modulation based notch filter with laser powers designed to minimise the passband ripples. Simulated response of the conventional microwave photonic notch filter based on MZI structure (dashes). (b) Measured responses of the tuneable three-wavelength double-pass modulation based notch filter for two different sets of laser wavelengths.

5. Conclusion

A microwave photonic notch filter structure that realises a narrow notch, wide passband, and low group delay ripple, has been presented. It is based on a WDM technique with a double-pass modulation approach incorporating sequentially spaced reflectors that provide the appropriate time delays for the remodulations to realise coincident notches at the desired notch frequency and flattened response at other passband frequencies. The notch can be further narrowed by increasing the number of laser-grating pairs. The design of the WDM laser powers to reduce the passband amplitude ripple and also the group delay ripple simultaneously, has been presented. Experimental results have demonstrated a high-resolution notch filter operation with tuneability and high SNR performance.

6. Acknowledgments

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