Photonics-Based Interference Mitigation Filters

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***Abstract*—New photonic filter structures for interference mitigation of microwave signals are presented. These fiber filters have a parallel topology, and comprise a grating based photonic bandpass filter, or a dual offset cavity structure based on a new noncommensurate delay-line approach. The new topologies overcome the problem of synthesizing both a narrow stopband and a very-wide and flat passband, to simultaneously excise interference with minimal impact on the wanted signal over a wide microwave range. Results demonstrate stopbands of around 1% of center frequency, wide-band flat transmission, and a shape factor of 10.5 that is the lowest reported for a photonic notch filter, in excellent agreement with predictions.**

***Index Terms*—Gratings, notch filters, optical fiber delay lines, optical filters, optical signal processing.**

I. Introduction

MICROWAVE photonic systems for the distribution of signals have been the subject of significant interest. This is driven by the high bandwidth capabilities of fiber-optic systems and also the ability to provide interconnect transmission properties that are virtually independent of length. Since in such fiber-optic systems the signal is already in the optical domain, the question arises: can the processing on the signal be done directly in the optical domain? It is highly attractive to incorporate photonic signal processing into the optical fiber network, because this has the potential of overcoming the existing electronic bottlenecks for processing high bandwidth signals, and it can also provide in-built signal conditioning that can be integrated with the fiber-optic system.

The ability to reject RF interference from signals that are carried in optical fiber is an important problem. In several applications such as in fiber-radio links and in phased array antennas, microwave fiber-optic systems carry not only the desired signal but also unwanted interfering signals that are picked up by the antenna. These interfering signals, which may be at high levels, can place undue demands on the dynamic range requirements of the fiber-optic link or on the resolution of the A/D converter if digital conversion is made. Photonic signal processing to excise the interfering signals has the potential to overcome this problem.

Several photonic notch filter structures have been reported [1]–[3]. However, these previous structures are limited to synthesizing only a few taps. Hence they have the drawback of producing a response that is much too gradual, causing significant frequency-dependent attenuation in the required passband, which can corrupt the wanted information signal itself. This makes such filter structures inappropriate for interference suppression. There have been no reports of a photonic filter that can satisfy the key requirements of interference mitigation filters, i.e., to simultaneously provide both a narrow excision band for rejecting RF interference and at the same time to transmit the wanted signal over a flat and wide passband and a large frequency range.

The objective of this paper is to present two new photonic filter structures that can fulfill these requirements. The first is a novel parallel topology photonic interference mitigation filter, which can synthesize a flat, broad passband and a very narrow notch. The second is a new type of filter that, in addition, significantly improves the squareness of the stopband response (or shape factor). This latter topology is novel in that it is based on a noncommensurate delay-line approach, which introduces a new class of filter with respect to previous photonic filter approaches that are based on commensurate delay-line techniques. This fiber-based filter comprises and offset cavity structure, and can provide an extremely flat response in the passband, together with a large reduction in the shape factor of the interference rejection band. Results are presented for these photonic interference mitigation filters that demonstrate stopbands of around 1% of center frequency, with very small shape factors, as well as notch depths of around 45 dB, and wide-band transmission with very low passband ripples, for high-resolution interference mitigation in fiber based transmission systems.

This paper is organized as follows. The new parallel topology photonic interference mitigation filter is described in Section II. The topology of the new fiber-based filter for interference mitigation with offset cavities, which can synthesize reduced shape factors, is presented in Section III. Finally, experimental results on these filters, which demonstrate the high resolution notch filtering and comparison with predictions, are described in Section IV.

II. Parallel Photonic Filter Topology

The topology of the new parallel fiber-based filter for interference mitigation is shown in Fig. 1. In this structure, the fiber-optic signal is split and routed into the following two paths: 1) a direct fiber path shown in the top part of Fig. 1 and 2) a parallel path, which contains a high-Q optical bandpass filter at center frequency f_o shown in the lower part of Fig. 1. Each output is detected using a photodiode in a balanced configuration so as to subtract the photocurrents and, hence, a notch filter characteristic is realized at frequency f_o. The direct path uses optical fiber to provide a broad-band all-pass structure for the RF

Manuscript received January 5, 2001; revised May 25, 2001. This work was supported in part by the CSIRO-ATNF and by the Major National Research Facility Program.

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Publisher Item Identifier S 0018-9480(01)08705-1.

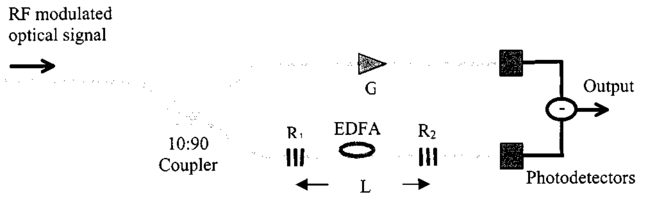

Fig. 1. The topology of the parallel fiber-based filter for interference mitigation.

signal. The parallel path requires a high-Q photonic bandpass filter. From several possible structures for this filter [4]–[6], we have employed a simple active fiber Bragg grating pair structure [4], but with an important modification in that the filter is operated in transmission mode rather than in reflection mode [4]. This eliminates the need for a circulator. The pump laser level sets the gain of the active erbium doped fiber section, and this sets the pole position and Q of the filter.

The transfer characteristic of the transmissive bandpass filter component shown in the lower arm of Fig. 1 is given by

$$H_{BPF}(z) = g(1 - R_1)(1 - R_2)\left[\frac{1}{1 - Uz^{-1}}\right] \quad (1)$$

where $U = g^2 R_1 R_2$, g is the gain of the EDFA and R_1 and R_2 are the grating reflectivities. The transfer function of the notch filter shown in Fig. 1 is given by

$$H(z) = 0.1G - 0.9\frac{g(1 - R_1)(1 - R_2)}{1 - Uz^{-1}}. \quad (2)$$

The all-pass gain G is chosen so that $H(z) = 0$ at $z = e^{j2\pi}$.

Therefore, G is given by

$$G = 9g(1 - R_1)(1 - R_2)\frac{1}{1 - U}. \quad (3)$$

Hence, from (2) and (3) the transfer function is

$$H(z) = 0.9g(1 - R_1)(1 - R_2)\left[\frac{1}{1 - U} - \frac{1}{1 - Uz^{-1}}\right]. \quad (4)$$

By making the pole of the active stage approach unity, the bandwidth of the notch can be narrowed. This also produces a very flat passband response. The delay length of the active section L is chosen to give a delay time corresponding to the filter design center frequency $\mathrm{f_o}$. The delay length of the direct path (upper arm) should be the same as the delay length through the parallel path that a pulse would see traveling through the lower arm.

The advantage of this structure is that it can synthesize a filter with a flat broad-band passband and a very narrow notch. The direct path can be extremely wide-band, exploiting the capabilities of fiber optics. Hence the response of the filter depends on the characteristics of the optical bandpass filter. The latter can be realized with very large Q values at microwave frequencies using photonic techniques. The subtraction process at the output produces extremely flat passband regions, and a very narrow stopband width of the overall filter that is similar to the narrowness of the photonic bandpass filter. Use of chirped gratings and wavelength tuning [7], in this structure also affords the possibility of extension to provide filter tunability.

However, a difficulty with this structure is that the squareness of the stopband response (or shape factor) may be inadequate for some applications. Here we define the shape factor as the ratio of the −6-dB bandwidth to the −35-dB bandwidth of the interference rejection filter.

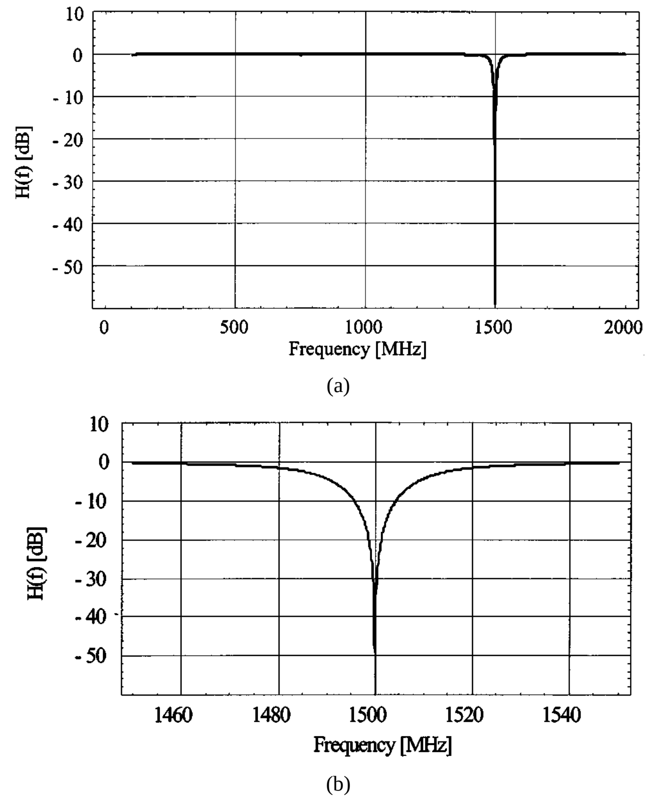

Fig. 2. Frequency response of the single-cavity photonic interference rejection filter. (a) Wide-band response. (b) Detailed section of response within 50 MHz of center stopband frequency.

$$\mathrm{SF} \equiv \frac{\mathrm{BW}_{-6\,\mathrm{dB}}}{\mathrm{BW}_{-35\,\mathrm{dB}}}. \quad (5)$$

The shape factor gives a figure-of-merit for the squareness of the interference rejection filter response, and its ideal value is unity. This filter topology produces a large shape factor. The reason for this is because the simple photonic bandpass filter has a single pole, which constrains its response shape characteristics so that the steepness of the transition skirt edges is not high enough.

As an example, we consider the design of an interference rejection filter with 1% bandwidth of the center frequency at 1.5 GHz, i.e., having a −6-dB stopband width of 15 MHz. The parameters are grating reflectivity $\mathrm{R}_1 = \mathrm{R}_2 = 0.78$ and erbium amplifier single pass gain of $\mathrm{g} = 1.247$. The resulting response is shown in Fig. 2. This displays a notch at 1.5 GHz. The passband is flat, and the passband transmission factor has no loss. The notch is deep, however the steepness of the transition skirt edges is not high enough, which causes the −35-dB width to be too small. The resulting shape factor for this interference rejection filter is 33, which may be too high for some applications.

III. Parallel Topology Photonic Filter With Dual Cavity

The topology of the new fiber-based filter for interference mitigation, which can synthesize significantly reduced shape

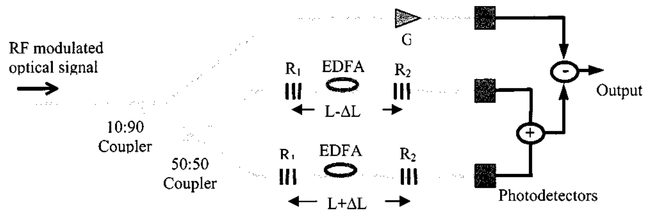

Fig. 3. New dual-cavity parallel topology fiber-based interference rejection filter.

factors, is shown in Fig. 3. The concept in this topology is to use two photonic bandpass filters, instead of the single one above. These two photonic filters are designed to be slightly detuned from the center frequency corresponding to the required notch frequency $\mathrm{f_o}$, and operate at frequencies $\mathrm{f_o} - \Delta\mathrm{f}$ and at $\mathrm{f_o} + \Delta\mathrm{f}$. This is shown by the different cavity lengths between the Bragg gratings of $\mathrm{L} + \Delta\mathrm{L}$ and $\mathrm{L} - \Delta\mathrm{L}$ in Fig. 3. The delay lengths in this case are slightly offset, hence, this topology is based on a noncommensurate delay-line approach, which is a new class of photonic filter technique. The two bandpass filter frequencies are slightly detuned from the fundamental frequency of the notch processor, so the combined response of the bandpass filters yields a squarer response and hence, after subtraction from the direct path, realizes a much lower shape factor for the notch filter.

The signal is split equally between the two offset bandpass filters, as shown in Fig. 3. The Q for both filters is controlled by the gain of the active erbium doped fiber section. Since these optical bandpass filters are operated in the transmission mode their outputs can be directly summed via the photodetectors. This combined response is subtracted from the all-pass direct path response, to yield a narrow-stopband filter response with a significantly reduced shape factor.

For the structure shown in Fig. 3, the transfer characteristic is given by

$$H(z) = 0.1G - 0.45g(1-R_1)(1-R_2) \cdot \left[\frac{1}{1-Uz^{k-1}} + \frac{1}{1-Uz^{-k-1}}\right] \tag{6}$$

where $U = g^2 R_1 R_2$, $k = \Delta\mathrm{L}/\mathrm{L}$.

The all-pass gain G is chosen so that $H(z) = 0$ at $z = e^{j2\pi}$. Therefore, G is given by

$$G = 4.5g(1-R_1)(1-R_2)\frac{2\left[1-U\cos(2\pi k)\right]}{1-2U\cos(2\pi k)+U^2}. \tag{7}$$

Hence, from (7) and (6) the transfer function is

$$H(z) = 0.45g(1-R_1)(1-R_2) \cdot \left[\frac{2\left[1-U\cos(2\pi k)\right]}{1-2U\cos(2\pi k)+U^2} - \frac{1}{1-Uz^{k-1}} - \frac{1}{1-Uz^{-k-1}}\right]. \tag{8}$$

In this structure, the active cavities introduce different poles. The position of each pole is principally controlled by the difference in cavity length, and by the EDFA gain and the reflectivities of the Bragg gratings $\mathrm{R_1}$ and $\mathrm{R_2}$. The zero is at $\mathrm{z_0} = \exp(\mathrm{j}2\pi)$, which corresponds to a notch frequency $f_o = 1/T = c/(2nL)$, where T is the round trip delay time corresponding to a cavity length L, n is the fiber refractive index, and c is the speed of light. The 6-dB bandwidth of the notch filter is mainly controlled by the cavity length difference and the EDFA gain. Since the poles are close to the unit circle, it is important to stabilize the EDFA gain and avoid gain fluctuations. This can be most simply achieved by designing the EDFA to operate in its saturation region so any fluctuation in the pump power has little effect on the gain. To increase the squareness of the stopband, it is required that the poles of the two bandpass filters are close to one another so that their combined response gives a flat top with steep edges. This ensures that the notch filter stopband is wider than that of the single cavity, while still producing negligible effect on the flatness of the passband response of the overall filter. The Bragg grating reflectivities can control the passband loss. Hence, one can optimize these reflectivities to give zero insertion loss for the interference mitigation filter. The delay length of the direct path (upper arm) should be the same as the delay length through both parallel paths that a pulse would see traveling through the lower arms. The length offset $2\Delta\mathrm{L}$ between the two active cavities adjusts the shape factor of the filter. This length offset is optimized to obtain the minimum shape factor. The coherence length of the optical source must be less than the double-pass length of the cavity 2L, to avoid coherent interference effects. The frequency range of this filter structure is limited by the frequency range of the microwave combiners, however practical wide-band microwave in phase and out of phase combiners to frequencies of over 20 GHz are available.[1]

As an example, we consider the design of the same interference rejection filter as in Section II, i.e., with 1% bandwidth of the center frequency at 1.5 GHz, i.e., having a −6 dB stopband width of 15 MHz. This relates to a requirement for fiber based notch filters for the Square Kilometer Array (SKA) [8] for the transmission of broad-band astronomy signals from a large number of SKA stations to a central site, and the removal of strong man-made interfering signals, such as satellite signals, from the astronomy bands.

In order to meet these requirements, the dual-cavity structure in Fig. 3 was designed with grating reflectivities of $\mathrm{R_1} = \mathrm{R_2} = 0.78$, fractional length detuning factor $\mathrm{k} = 0.0047$, and erbium amplifier single pass gains of $\mathrm{g} = 1.27$. The frequency response of this fiber-based interference rejection filter is shown in Fig. 4. The notch frequency is at 1.5 GHz. The passband is flat within 0.1 dB, and the passband transmission factor has no loss. A detailed section of the frequency response, within 50 MHz of the center stopband frequency is displayed in Fig. 4(b). The 6-dB width of the stopband of the filter is 15 MHz. The shape factor for 35-dB rejection is 5.8 for this structure. This achieves a large improvement, giving a 5.7 times smaller shape factor in comparison to the simple single-pole photonic notch filter of Fig. 1 which had a shape factor of 33. Regarding the noise added in the passband, the principal contribution is the phase-noise-induced intensity noise [9]. An analysis for the phase-induced intensity noise of the bandpass filters in each arm shows that this noise peaks at the bandpass frequency, however it is quite low in the

[1]See for example microwave combiners at Microwave Communications Laboratories Inc.

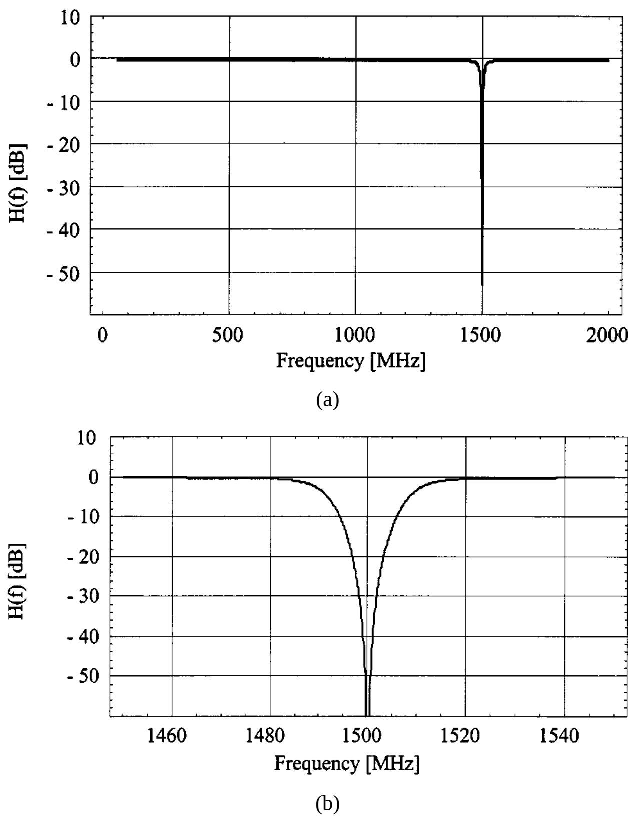

Fig. 4. Frequency response of the dual-cavity photonic interference rejection filter. (a) Wide-band response. (b) Detailed section of response within 50 MHz of center stopband frequency.

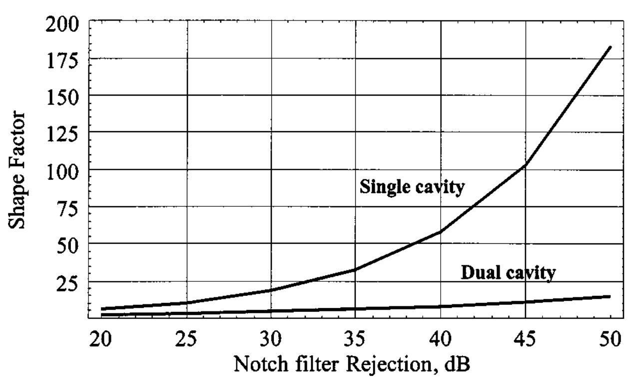

Fig. 5. Stopband filter shape factor versus rejection level.

out of band frequency regions [10]. Since the passband of the notch filter corresponds to the out of band regions of the band-pass filters in the arms, the noise added in the passband of the notch filter is quite low.

The results above have been given for a particular rejection level of 35 dB. A comparison between the shape factor of the single cavity filter and the dual-cavity filter versus rejection levels is shown in Fig. 5. This is shown for a 1.5-GHz filter with a stopband width of 15 MHz. It can be seen that the dual-cavity topology enables a large improvement in shape factor to be obtained. This is especially the case at the higher rejection levels, where the single cavity shape factor rapidly deteriorates, whereas the dual-cavity structure can provide a low shape factor performance over a wide range of rejection levels.

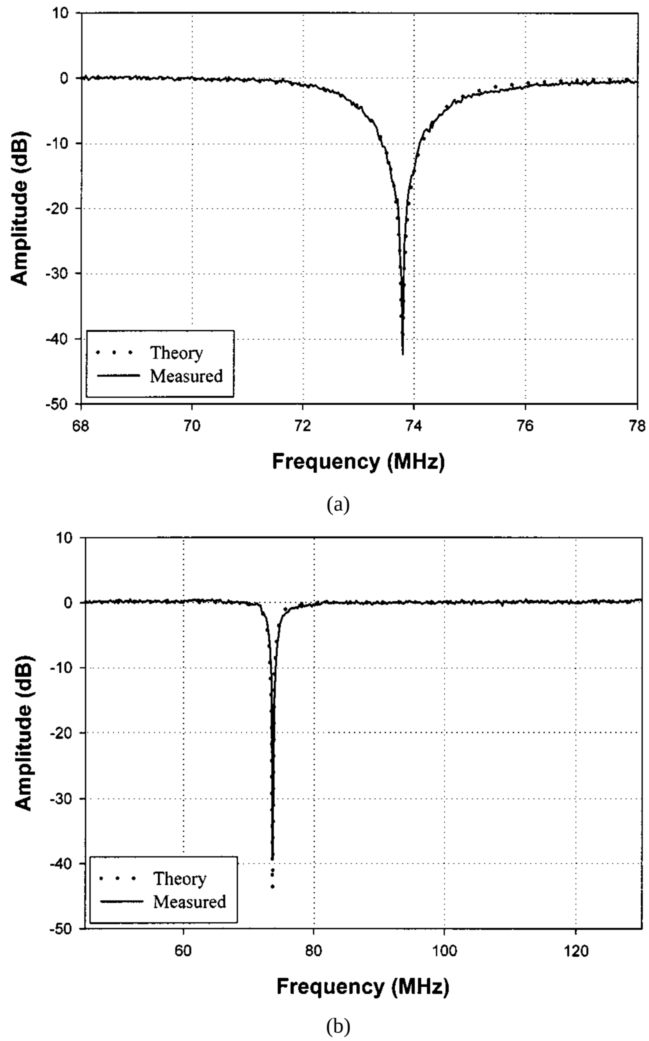

Fig. 6. Comparison between the measured and predicted frequency response for the single cavity photonic interference rejection filter. (a) Detailed section of response within 10 MHz span around the center stopband frequency. (b) Wide-band response.

It can be seen that the architectures shown in Figs. 3 and 1, basically comprise couplers, gratings and erbium amplifiers, which is suitable for integration using planar lightwave circuit technology. Couplers and gratings have been demonstrated on silica planar circuits, and the architectures require only very low erbium amplifier single pass gain of around 1–3 dB. Such gains can readily be realized in planar integrated amplifiers, for example, 3.5 dB of gain can be obtained using a short length of only 1.5 cm in Er–Yb codoped waveguide amplifier [11], which shows the potential of integrating this architecture on a substrate.

IV. Experiment and Results

In order to verify the proof of principle for the new topologies described above, two experimental photonic filters were set up. The first filter was the single cavity parallel fiber-based filter structure shown in Fig. 1. The second filter was the dual-cavity noncommensurate delay-line filter with offset cavity lengths corresponding to the structure shown in Fig. 3. The experiments were aimed to show the proof of principle for the filters, and as such they were carried out for a relatively low notch center

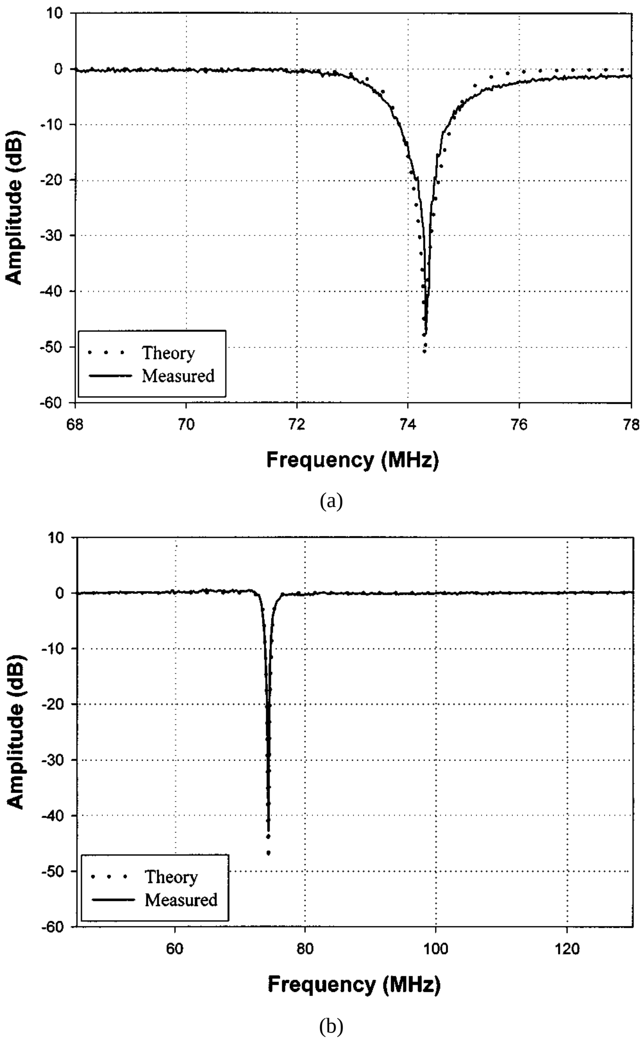

Fig. 7. Comparison between the measured and predicted frequency response for the dual-cavity photonic interference rejection filter. (a) Detailed section of response within 10 MHz span around the center stopband frequency. (b) Wide-band response.

frequency of 74 MHz for simplicity and ease of measurement, however they provided a demonstration to verify the concepts. Both these photonic interference rejection filters were designed to have a notch bandwidth of around 1.8% of center frequency. Bragg gratings at 1541 nm with 50% reflectivity were used to form the cavities in all the filter structures. The cavity length for these filters was 139.8 cm. In the case of the single cavity filter, the erbium amplifier gain was 1.95. In the case of the dual-cavity filter, the erbium amplifier gains were 1.97 and the fractional length detuning factor k was 0.007, which corresponded to a length offset between the two cavities of 2.0 cm.

A comparison between the measured and predicted frequency response for the single cavity photonic interference rejection filter is shown in Fig. 6. Excellent agreement can be seen. The measured shape factor of this filter is 40, its notch bandwidth is 1.7% of center frequency, and the notch depth is 43 dB. A comparison between the measured and predicted frequency response of the dual-cavity photonic interference rejection filter is shown in Fig. 7. The measured shape factor for this filter is 10.5 in excellent agreement with the predicted shape factor of ten, the notch depth is 47 dB, and its notch bandwidth is 1.9%. This demonstrates a large improvement, giving a fourfold reduction in shape factor in comparison to the single cavity filter. Excellent agreement can be seen between the measured and predicted filter frequency response characteristics shown in Fig. 7.

V. Conclusion

Two new photonic filter topologies have been presented for interference mitigation of microwave signals. A novel parallel topology comprising a single grating based photonic bandpass filter has been described, which can synthesize a flat, broad passband and a very narrow notch. In addition, a new type of filter that is based on a noncommensurate delay-line approach and comprises a dual offset cavity structure has been described, which significantly improves the squareness or shape factor of the stopband response. To our knowledge, these are the first photonic filter structures that can synthesize both a narrow stopband and a very-wide and flat passband, to simultaneously excise interference with minimal impact on the wanted signal over a wide microwave range. The filtering techniques have been experimentally verified, and results have been presented for these photonic interference mitigation filters that demonstrate stopbands of around 1% of center frequency, as well as notch depths of around 45 dB, and wide-band transmission with very low passband ripples. For the dual-cavity filter structure, a shape factor for −35-dB interference rejection of 10.5 was obtained, which is the lowest reported for a photonic notch filter. These structures are readily extendible to operate at any required microwave frequency, and can also be implemented in planar lightwave circuit technology. Excellent agreement between measured and predicted responses was shown. The new photonic-based filters offer high-resolution interference mitigation, which can be integrated in optical fiber microwave transmission systems.

Acknowledgment

The authors would like to extend their thanks to Dr. P. Hall and N. You for valuable discussions.

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