A Novel Tunable Microwave Optical Notch Filter

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***Abstract*—A new topology for a tunable microwave photonic notch filter, which achieves a wide and continuous tuning range of FSR/2, is presented. The novel principle of tuning is based on changing optical variable attenuators only; consequently, a fixed wavelength laser can be used as the optical source. Experimental filter tuning results demonstrate a wide fractional tuning range of 50%, continuous tuning capability, and a notch filter shape that does not change as it is tuned, in very good agreement with predictions.**

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

I. Introduction

OPTICAL delay line architectures allow processing of high-frequency signals directly in the optical domain, thus exploiting the large bandwidth, low loss, and immunity to interference that is inherent in optical fibers. This enables a large time–bandwidth product capability and the ability to realize signal conditioning functions such as filtering with adaptive operation.

There has been considerable interest in photonic processing for microwave filtering applications, and several techniques for obtaining tunable microwave optical filters have been proposed [1]–[5]. These previous techniques are all based on the fundamental principle of tuning the wavelength of the laser source and using wavelength-selective elements to change the basic delay time of the discrete time processor, which consequently tunes the filter center frequency. Tuning of the delay length by means of wavelength tuning can be achieved using wavelength-selective elements such as high-dispersion fiber [1], [2], chirped gratings [3], [4], or arrayed waveguide gratings [5]. However, these approaches have some limitations. First, they require a wavelength-tunable laser, which may not be available in microwave fiber optic links using a fixed wavelength laser. Second, changing the delay time of the discrete time processor to tune frequency, which is the principle on which these approaches are based, actually changes the free spectral range (FSR) of the processor. Hence, the filter 3-dB width changes as its center frequency is tuned. Finally, because large time-delay changes are needed particularly for tuning at lower frequency ranges, long dispersive elements are needed, which can limit the tuning range. There have been no reports of a tuning method which works with a fixed wavelength laser and which produces a filter characteristic that maintains its shape independent of tuning.

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In this paper, we report a new topology for a tunable microwave photonic notch filter that overcomes these limits. Our structure requires only a fixed wavelength laser source. The novel principle of tuning is based on changing optical variable attenuators only, i.e., only amplitudes are changed. An advantage of this technique is that the filter shape and its bandwidth do not change as it is tuned, so the filter width does not increase at it is tuned to higher center frequencies. Moreover, a wide and continuous tuning range is realizable, without the need for special dispersive elements. Using this new topology, we report a widely and continuously tunable microwave optical notch filter.

This paper is organized as follows. The new topology for the tunable microwave photonic notch filter is presented in Section II. The analysis of the tuning range of this structure is described in Section III. Finally, experimental results on the tunable processor are described in Section IV, which demonstrate the wide and continuous tuning capabilities of the tunable notch filter.

II. Microwave Photonic Filter Tuning Principle

We consider a simple two-tap microwave optical notch filter. The transfer function of this filter is given by

$$H(f) = \cos(2\pi f T + \varphi) \tag{1}$$

where T is the time delay between the two optical taps.

The conventional way of tuning the notch frequency is to change the delay time T of the processor [1]–[5], by using a tunable laser and wavelength-selective elements. From (1), it can be seen that changing T not only tunes the notch frequency, but it also changes the FSR and the 3-dB notch bandwidth of the filter.

However, inspection of (1) shows that the notch frequency can also be tuned by changing φ. This results in a tunable filter, whose FSR and 3-dB notch bandwidth are maintained independent of tuning. In our new tunable filter topology, we change φ by means of an amplitude control technique. Compared with wavelength tuning, attenuation tuning with a fixed laser source has several advantages in realizing tunable optical signal processors. First, the tunable filter can be implemented at the receiver side of an optical link, independent of the laser source. Hence, if there are several users, each can independently control the filtering function according to individual requirements. This is also important because if a user wants to tune the filter frequency, there is no need to provide a return link to control the laser wavelength. Also, wavelength is a valuable resource in a multi-channel link, and attenuation tuning does not require spectral allocations that can reduce capacity. Moreover, changing attenuation of a variable optical attenuator can be accomplished

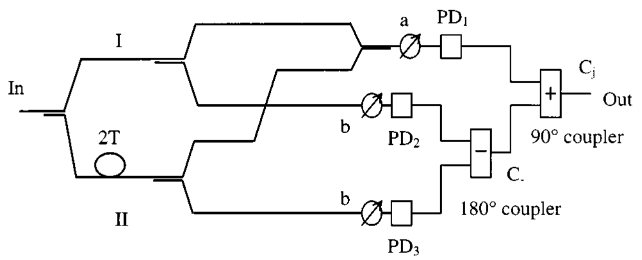

Fig. 1. Topology of the tunable microwave photonic notch filter.

with high precision and resolution. By comparison, wavelength tuning requires accurate delay length changes, which has difficulties at low frequencies because of the requirement of long chirped gratings and also has practical difficulties at high frequencies due to group delay scatter over a short grating length.

We realize φ tuning and notch frequency tuning by means of an amplitude control technique as follows.

Using the trigonometric identity, $\mathrm{H(f)}$ can be written as

$$H(f) = \cos(2\pi fT)\cos(\varphi) - \sin(2\pi fT)\sin(\varphi). \quad (2)$$

We let

$$a = \cos(\varphi)$$
$$b = \sin(\varphi). \quad (3)$$

Hence, from (2), the transfer function $\mathrm{H(f)}$ can be written as

$$H(f) = \frac{a}{2}\left(e^{j2\pi fT} + e^{-j2\pi fT}\right) - \frac{b}{2j}\left(e^{j2\pi fT} - e^{-j2\pi fT}\right). \quad (4)$$

We next take the z transform of the equation, using the relation

$$z = e^{j2\pi fT}. \quad (5)$$

Hence, the transfer function of the filter in the z domain is given by

$$H(z) = \frac{a}{2}\left(z + z^{-1}\right) + j\frac{b}{2}\left(z - z^{-1}\right). \quad (6)$$

The transfer function $\mathrm{H(z)}$ is the response of the RF signal field. Its amplitude response is given by

$$|H(z)| = \frac{1}{2}\left|a \cdot (1 + z^{-2}) + jb \cdot (1 - z^{-2})\right|. \quad (7)$$

We realize this function by means of the new topology, shown in Fig. 1. The terms 1 and z^{-2} represent optical paths with a relative time delay difference of $2T$. This is implemented by splitting the input RF modulated optical signal into the two arms I and II of Fig. 1, which have a delay difference of $2T$. An advantage of this microwave/photonic implementation over a purely microwave implementation of the filter structure is that it is difficult to realize high-quality delays using purely microwave implementations for the $2T$ delay without dispersion and frequency and length-dependent loss at microwave frequencies [6]. Another advantage of the microwave/photonic implementation is that it is compatible with processing signals that are already in the optical domain. In Fig. 1, the weighting terms a and b are realized by means of variable optical attenuators, which implement coefficients varying from 1 (corresponding to no attenuation) to 0 (corresponding to infinite attenuation). For the first term in the function, $a(1 + z^{-2})$ is realized by summation of the weighted direct and delayed optical signals at photodetector PD1. For the second term in the function, $b(1 - z^{-2})$ is realized by detecting the weighted direct and delayed optical signals and subtracting in the RF domain by means of a balanced detection technique. Finally, the quadrature summation of the a term with the jb term is obtained using a quadrature 90° microwave hybrid coupler, shown as $\mathrm{C_j}$ in Fig. 1. The transmission line lengths are made equal so that an input pulse traversing the direct path I via PD1 and PD2 would arrive at the output at the same time, and similarly an input pulse traversing the $2T$ delayed path II via PD1 and PD3 would arrive at the output at the same time. The frequency range of this filter is limited to the frequency range of the microwave components (i.e., the 90° and 180° phase-shift microwave couplers); however, practical wideband microwave 90° and 180° couplers to frequencies of over 20 GHz are available.[1] With reference to Fig. 1, the coherence time of the optical source must be less than the delay time $2T$ to avoid coherent interference effects when recombination occurs in the path containing a. Regarding noise, the principal element is the phase-induced intensity noise. The structure shown in Fig. 1 comprises nonrecursive passive delay lines. Moreover, there are only two paths, namely those that are recombined at a, which can contribute to phase noise. Hence, the noise properties of this filter are the same as the feed-forward Mach–Zehnder delay line structure that has been previously analyzed [7], [8], which shows that, because this is a passive structure comprising only two taps, the phase noise is small.

We have investigated the sensitivity of the filter response to length mismatches in the relative lengths of the four fiber propagation delay paths that comprise the filter structure. This has shown two effects. First, if any of the four path lengths is mismatched, this degrades the realizable notch depth but has a negligible effect on the notch frequency. The largest degradation occurs at the mid-tuning frequency, and, for this case, in order to ensure that a notch depth of at least 30 dB is obtained, it is required that the mismatch in a path length does not exceed the value corresponding to 2.5% of the delay time $2T$. Second, if any pair of the path lengths is mismatched, a shift in the notch frequency is produced. The notch frequency shift occurs because the FSR changes. A given percentage of $2T$ change in a pair of path lengths produces the same percentage change in notch frequency, e.g., a 2.5% of $2T$ change in any pair of path delays causes a 2.5% change in notch frequency.

III. Tuning Range

The notch frequencies of this filter are given by

$$f_{\text{notch}} = \frac{1}{2\pi T}\left[(2n+1)\cdot\frac{\pi}{2} - \varphi\right], \qquad \mathrm{n} = 0, 1, 2, \ldots . \quad (8)$$

Changing φ will tune the notch frequency. The required values of the optical attenuator settings a and b in Fig. 1 to obtain a

[1]See, for example, microwave combiners at Microwave Communications Laboratories Inc., St. Petersburg, FL.

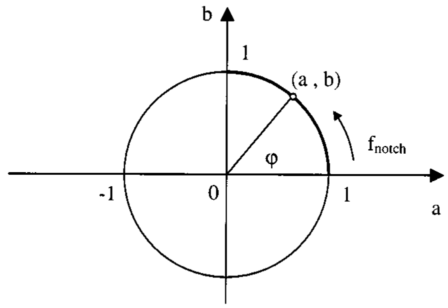

Fig. 2. Relationship between optical attenuator settings a, b, and φ.

given notch frequency are given by (3), which relates these coefficients to the tuning angle φ. It can be seen that, if drawn in a plane, a and b are located on the unity circle while φ corresponds to the angle of the point (a, b), as shown in Fig. 2.

We consider the positive quadrant of Fig. 2, which corresponds to both a and b being positive. This is the case for tuning using variable optical attenuators, because both a and b are optical transmissions coefficients, hence each of their ranges is limited to a value in the range 0 to 1. It can be seen that as (a, b) is changed across its full range from (1, 0) to (0, 1) on the unity circle, φ is tuned from 0 to $\pi/2$. The transfer function $\mathrm{H(z)}$ [and $\mathrm{H(f)}$] given in (6) and (7) is the amplitude response. The response of the RF signal power is proportional to the square of $\mathrm{H(f)}$

$$H_{\mathrm{RF}}(f) = H^2(f) = \cos^2(2\pi f T + \varphi). \tag{9}$$

Hence, as φ is tuned from 0 to $\pi/2$, $\mathrm{H_{RF}(f)}$ is tuned over a range of FSR/2. This tuning is realized by adjusting the attenuation of the optical attenuators in accordance with the coefficients a and b. An advantage of this tuning scheme over previous conventional tuning schemes that rely on changing the delay time T of the processor [1]–[5] is that the 3-dB bandwidth of the filter remains constant while tuning over a range of FSR/2, whereas in the delay time changing approach the 3-dB bandwidth fundamentally increases by 50% while tuning over the same range. Moreover, the wavelength-tuning scheme changes the FSR of the delay line processor, which means that unwanted filtering responses (such as additional notches) are introduced at different frequencies when the filter is tuned to a lower frequency and its FSR is decreasing. The attenuation-tuning scheme has a fixed FSR and the frequency response is tuned without changing its shape or introducing unwanted filtering responses at lower frequencies. Also, this technique has the ability to extend to bandpass filtering and an increase in the number of taps. By the same principle, each pair of optical taps in the time-domain response of a bandpass filter can be individually tuned by a structure similar to the one shown above, to tune the bandpass filtering function.

Tuning speed using the variable optical attenuators can be in the hundred-microsecond range.[2] Faster tuning in the subnanosecond range can be obtained by using semiconductor optical amplifiers as the variable gain elements.

[2]See, e.g., variable optical attenuators at Corning Inc., Corning, NY.

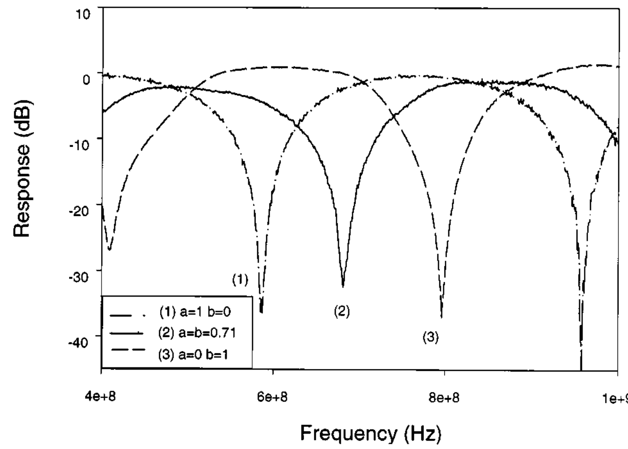

Fig. 3. Measured frequency responses when the notch filter is tuned.

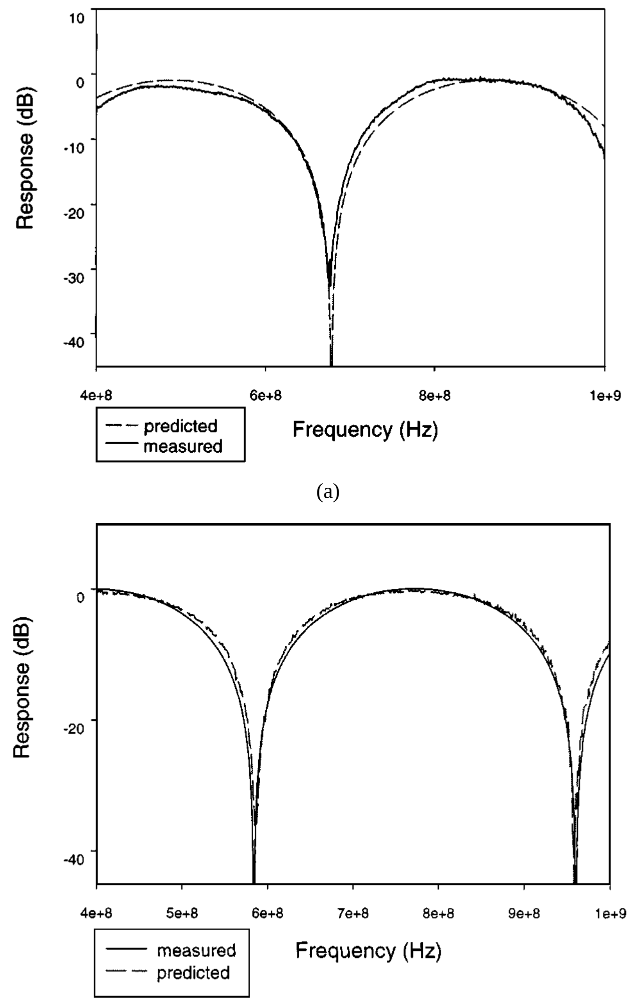

Fig. 4. Comparison between the measured and predicted notch filter response. Optical attenuator settings: (a) a = 0.71, b = 0.71 and (b) a = 1, b = 0.

IV. Experiment and Results

The tunable notch filter topology shown in Fig. 1 was set up to measure its tuning characteristics. The tunable filter was designed to operate in the 0.5–1-GHz range because of the microwave couplers used in the experiment; however, this can easily be extended to other frequencies if components with other frequency ranges are used in the system. The optical delay length difference, denoted by 2T in Fig. 1, was 55 cm, corresponding to an FSR of around 380 MHz in the frequency response of the processor.

The measured frequency response of this tunable notch processor is shown in Fig. 3. Curve 1 shows the response for the optical attenuator settings of $a = 1$ and $b = 0$, which corresponds to one of the limits of the tuning range. Curve 2 shows the response for an intermediate tuning state corresponding to optical attenuator settings of $a = b = 0.71$. Finally, curve 3 shows the response for the optical attenuator settings of $a = 0$ and $b = 1$, which corresponds to the other limit of the tuning range. The slightly reduced notch depth characteristic for Curve 2 is believed to be due to the nonideal phase characteristics of the quadrature microwave hybrid.

Fig. 3 shows that a tuning range of around 190 MHz has been obtained. This corresponds to a frequency-tunable range of FSR/2, as predicted. These results demonstrate a fractional tuning range of 50%, which shows the wide tunability together with continuous tuning capability of this filter structure. In addition, the shape of the notch filter response effectively does not change as its center frequency is tuned. The delay lengths of the structure used in the experiment were characterized from the setup. Fig. 4 shows a comparison between the measured and predicted notch filter response. This is displayed for two representative tuning conditions corresponding to the optical attenuator settings shown. Very good agreement can be seen between the measured and predicted results.

V. Conclusion

A new topology for a tunable microwave photonic notch filter has been presented. This achieves a wide filter frequency tuning range of FSR/2, together with continuous tuning capability. The novel principle of tuning is based on changing optical variable attenuators only and utilizes an amplitude control technique. Because the tuning is not realized by changing the delay length, as with previous approaches, no wavelength-tunable lasers are required and no dispersive optical components are needed. This has the advantage that a fixed wavelength laser source can be used in the tunable filter structure. In addition, this technique results in a filter shape and bandwidth that does not change as it is tuned, so the filter width does not increase at it is tuned to higher center frequencies. Moreover, a wide and continuous tuning range is realizable, without the need for long dispersive elements. We have experimentally verified the tuning technique by demonstrating a tunable microwave photonic notch filter. This exhibited a wide fractional tuning range of 50%, continuous tuning capability, and a notch filter shape that did not change as its frequency is tuned. Comparison between measured and predicted responses showed very good agreement. The novel tunable notch filter topology has potential in RF filtering applications that require wide and continuous notch tuning range.

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