# Microwave Optical Filters Using In-Fiber Bragg Grating Arrays

D. B. Hunter and R. A. Minasian

***Abstract*—A novel multitap optical transversal signal processor based on wavelength multiplexed Bragg grating arrays is presented. This structure enables the realization of a large number of taps for obtaining sharp bandpass filtering with high resolution and also enables arbitrary tap weight profiles to be obtained. Results on a 4-GHz, 29-tap filter demonstrates a sharp bandpass filter response, and windowing techniques on the tap profiles are demonstrated to enhance the sidelobe suppression characteristics.**

## I. Introduction

FIBER-OPTIC signal processors based on transversal filter structures have attracted considerable attention because they offer the capability of manipulating high speed signals directly in the optical domain before transduction into electrical signals. Recently, several structures have been reported for fiber-optic microwave tapped delay line filters [1]–[3]. However, high resolution bandpass filtering with sharp response requires a large number of controllable taps, and a structure that can realize this is necessary.

This letter presents a novel fiber-optic microwave transversal filter. It is based on two new concepts. These comprise a wavelength multiplexed intra-core Bragg grating array that functions as the tapping elements and a broadband spectral light source derived from the amplified spontaneous emission of erbium-doped fiber. This structure has the advantages that it is readily scalable to a large number of taps, is simple to implement, and is versatile in enabling shaping of the tap element profile to obtain windowing for the design of the filter response. Using these techniques, we present results for microwave optical bandpass filters that demonstrate sharp responses with side-lobe suppression employing windowing.

## II. Wavelength-Multiplexed Rainbow Transversal Filter

The experimental setup for the microwave optical transversal filter is shown in Fig. 1. This consists of a broadband optical source that is intensity modulated by an electrooptic modulator, and which is incident on the grating array, placed on both ports of a 3-dB coupler. The Bragg grating array forms the tapping elements of the transversal filter, which functions by reflecting a slice of the modulated light. Each Bragg grating was written at a slightly different Bragg wavelength in the 1540–1560 nm range and was written at regular intervals along the length of a single mode optical fiber. The optical source, which comprises broadband amplified spontaneous emission (ASE), was obtained by reverse pumping an aluminosilicate erbium-doped fiber. The spectral output of this source is relatively flat within the 1540–1560 nm range, hence the signals reflected from the grating array are approximately the same strength. The individual gratings had a reflectivity of 60% and a reflection bandwidth of approximately 0.35 nm. The insertion loss of the system can be made small through the use of a preamplifier ahead of the electrooptic modulator.

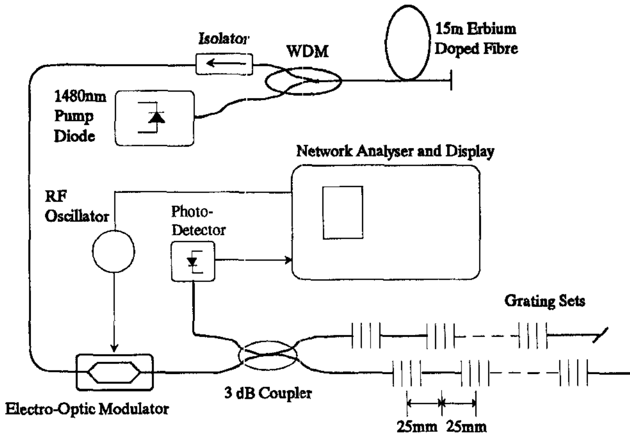


Fig. 1. Experimental setup.

By using a broadband source and a “rainbow” of Bragg gratings that span the range of this source, we form a series of noninteracting taps where the reflectivity of the individual gratings determines the tap weights and the separation between them gives the delay. The successively delayed and tapped reflected signals from each grating in the array is coherently summed in terms of the modulation envelope at the photodetector, and the transfer function of the filter is displayed on the network analyser.

This structure has advantages over previous approaches that use single wavelength taps with a single optical source [2], [3], because it eliminates the need to use very low reflectivity taps (in the order of a few percent) and avoids the progressive shadowing effects that taps further from the source experience due to preceding reflectors. In the present approach, the taps are written at different discrete wavelengths and a broadband optical source is used that enables strong reflectors to be used without any shadowing effects between successive taps. This is important for the realization of a large number of taps.

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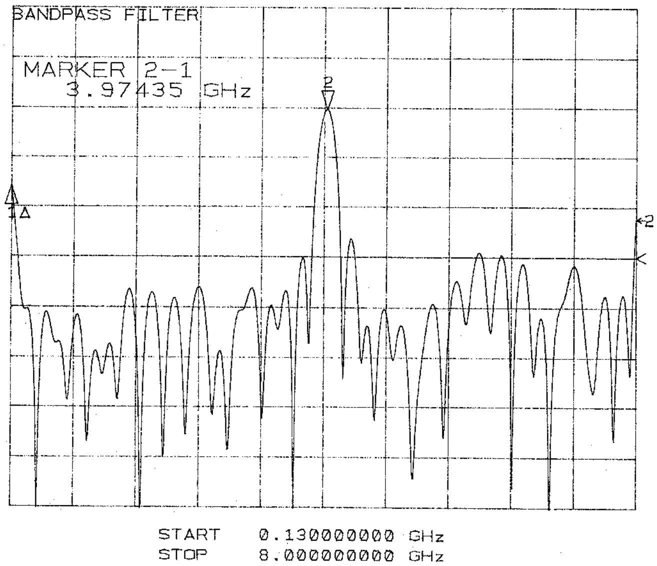


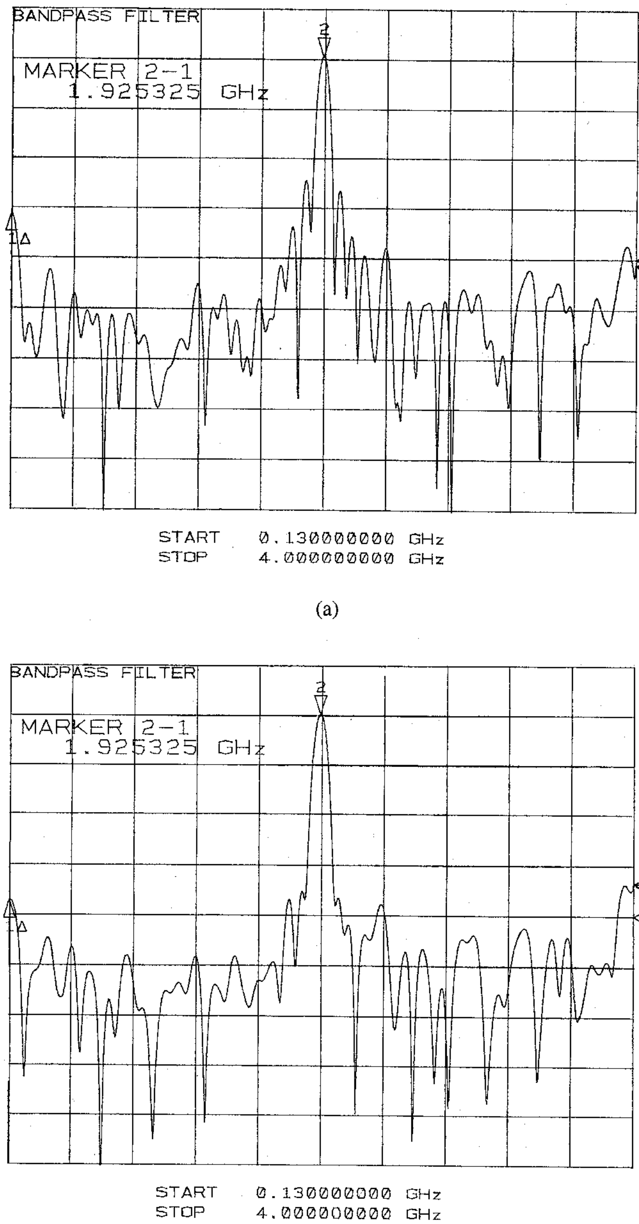

Fig. 2. Measured frequency response of 29-tap transversal filter with tap spacing of 25 mm. Vertical scale is 5 dB/div.

## III. Results

A transversal filter comprising 29 taps as shown in Fig 1. was constructed and tested. Time domain response measurements of the impulse response showed a grating spacing of 25 mm. The filter frequency response, measured using a network analyser, is shown in Fig. 2. This demonstrates a bandpass filter centre frequency of 4 GHz, in agreement with theory. The main sidelobes are around $-13.5$ dB as expected for the nominally rectangular window of the impulse response. The intermediate sidelobes show some nonuniformity, which is due to small variations in the grating reflectivities and spacing.

For some applications, it may be desirable to further reduce the sidelobes of the filter response by windowing the impulse response. While optical fiber transversal filter topologies have been reported based on coupler structures [4] that can produce a large number of taps, these are not suitable for windowing because they produce equal taps and hence the sidelobe levels cannot be reduced. However, the present structure not only enables many taps to be obtained but also provides a windowing capability by controlling the relative amplitudes of the reflective taps. This can be done by controlling the spectrum of the broadband optical source or by tapering the reflectivity of the gratings using post-processing techniques.

An example of a microwave optical transversal filter with windowing is shown in Fig. 3. This shows a 29-tap filter with a center frequency of 2 GHz. Fig. 3(a) displays the equal tap or rectangular window response. The measured mainlobe width, defined as the symmetric distance between the central zero crossings, is 147 MHz, which is in good agreement with the predicted value of 133 MHz. Fig. 3(b) shows the response of the filter when the window is tapered smoothly by controlling the amplitudes of the reflective taps. With reference to the




(b)

Fig. 3. Measured frequency response of 29-tap transversal filter with tap spacing of 50 mm. (a) Rectangular weighting. (b) Tapered weighting, tapering parameter $\beta = 1.9$. Vertical scale is 5 dB/div.

Kaiser window description

$$w[n] = \begin{cases} \dfrac{I_0[\beta(1-[(n-\alpha)/\alpha]^2)^{1/2}]}{I_0(\beta)} & 0 \le n \le M \\ 0, & \end{cases}$$

where $M$ = number of taps, $\alpha = M/2$, and $I_0(\cdot)$ represents the zeroth-order modified Bessel function of the first kind, the tapering parameter in Fig 3(b) is $\beta = 1.9$. The measured mainlobe width is 178 MHz, which is in good agreement with the theoretical value of 166 MHz [5]. The small difference between measured and predicted width is due to slight irregularities in the individual grating reflectivities and the spacing between the gratings. The main sidelobe levels are at $-18$ dB, which represents a 5-dB improvement relative to Fig. 3(a). Further sidelobe reduction may readily be obtained by increasing the tapering.

## IV. Conclusion

A novel microwave optical transversal signal processor based on wavelength multiplexed Bragg grating arrays has been demonstrated. This structure features the capability of realising a large number of taps to obtain bandpass filtering with high resolution. A 4-GHz, 29-tap filter has been demonstrated, which to our knowledge is the highest reported for a reflectively tapped optical transversal filter. This topology is scalable to a large number of taps by using a $2 \times N$ coupler and can operate up to millimeter-wave frequencies. In addition, it enables arbitrary tap weight profiles to be realized, and windowing techniques to realize bandpass filtering with improved sidelobe suppression has been demonstrated. This offers high resolution microwave optical filtering with high time-bandwidth operation.

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## References

[1] A. H. Quoc, and S. Tedjini, "Experimental investigation on the optical unbalanced Mach-Zehnder interferometers as microwave filters," *IEEE Microwave and Guided Wave Lett.*, vol 4, no. 6, pp. 183–185, 1994.

[2] S. Gweon, C. E. Lee, and H. F. Taylor, "Wide-band fiber optic signal processor," *IEEE Photon. Technol. Lett.*, vol 1, pp. 467–468, 1989.

[3] D. B. Hunter and R. A. Minasian, "Reflectively tapped fibre optic transversal filters using in-fibre Bragg gratings," *Electron. Lett.*, vol. 31, no. 12, pp. 1010–1012, 1995.

[4] C. C. Wang, "High-frequency narrow-band single-mode fiber-optic transversal filters," *J. Lightwave Technol.*, vol. 5, no. 1, pp. 77–81, 1987.

[5] J. F. Kaiser and R. W. Schafer, "On the use of the I0-sinh window for spectrum analysis," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 28, no. 1, pp. 105-107, 1980.