# Photonic Signal Processing of Microwave Signals Using an Active-Fiber Bragg-Grating-Pair Structure

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***Abstract*— A new active photonic signal processor which achieves a high-$Q$ microwave bandpass response if presented. It comprises active fiber within a pair of fiber Bragg gratings, and produces multiple taps with precise delay-time characteristics. The impulse response has demonstrated well in excess of 270 taps. The filter response demonstrates high resolution, having a narrow-band response with a $Q$ of 325. The processor is also tunable, in both passband width and frequency.**

***Index Terms*— Fiber Bragg gratings, microwave photonics, photonic signal processing, optical delay-line filters.**

## I. Introduction

OPTICAL-FIBER tapped-delay-line processors are attractive for microwave signal-processing functions because of their advantages of very high time-bandwidth product operation [1], [2]. These processors can overcome limitations imposed by conventional electrical signal processors, which are limited in sampling speed [3]. In addition, photonic processors offer excellent isolation, high resolution, insensitivity to interference and crosstalk, and also have adaptive capabilities. Thus, moving beyond its role as a passive transmission medium for broad-band signals, optical fiber can also be viewed as an optical network that is capable of performing high-speed processing tasks on the signals that are contained within the fiber. For these reasons, there is considerable interest in photonic systems for a number of frequency- and time-domain applications, such as microwave filtering, frequency discriminators, channel selectors, fast signal correlation, matched filtering, and programmable delay lines.

Many applications require a high-frequency (HF) selectivity and high-$Q$ processors. This requires many taps, and also precise weights and very precise delay spacings. Hence, it is important to develop structures which can produce a large number of taps in order to realize sharp-frequency-response characteristics and high resolution in the frequency domain. Several structures have been reported for optical transversal filters [3]–[10], however, these are limited to a small number of taps (around 20), as they require as many components as there are taps. Nevertheless, high-$Q$ bandpass filters require a large number of taps ($\gg 100$), which must also have precise weights and very precise delay spacing.

The tapping technique is a key to the operation of these processors. Various structures have been investigated, including high dispersion fiber [3]–[5], unbalanced Mach–Zehnder structures [6], [7], and mirror reflectors [8]. Recently, photonic delay-line signal processors have been demonstrated, which utilize fiber Bragg gratings [9]–[11]. Intracore fiber gratings, whose reflectivity controls the tap weights, and whose spacing controls the time delay, open up new possibilities for optical transversal delay-line processors. As well as providing the ability to realize precise taps or samples of the input signal, they provide the ability of attaining short delays and high sampling frequency. Also, the well-defined spectral wavelength selectivity of gratings offers the possibility of tuning the processor function. Bragg gratings also feature high-efficiency sampling, controllability, design precision, and compatibility with optical waveguides [12].

This paper presents a new active optical-transversal filter structure, which utilizes only two fiber Bragg grating reflectors, yet is capable of producing a very large number of taps with precise delay characteristics, and results in a very narrow-band filter response. This comprises a novel topology of an active optical-gain section in conjunction with grating sampling elements. A Bragg grating pair with a gain medium recirculates the signal back and forth, reflecting off the same gratings many times. This active grating structure can produce a very large number of taps ($\gg 100$) and can achieve large-$Q$ values and high resolution.

The active grating-based delay-line filter structure for photonic signal processing of microwave signals is presented in Section II. Results are given in Section III for the impulse and frequency response of the filter, which demonstrate multiple-tap high-$Q$ characteristics, and extensions to tunable operation are described.

## II. Active Grating-Based Tapped-Delay-Line Filter

The structure for the optical tapped-delay-line microwave-signal processor is shown in Fig. 1. This comprises a section of active fiber within a pair of fiber Bragg gratings. The first grating upon which the modulated lightwave carrier is incident, grating #1, has a reflectivity of 50%, while the second one, grating #2, has a reflectivity of 100%. The modulated light incident on the grating pair comes from a laser whose coherence time is less than the transit time

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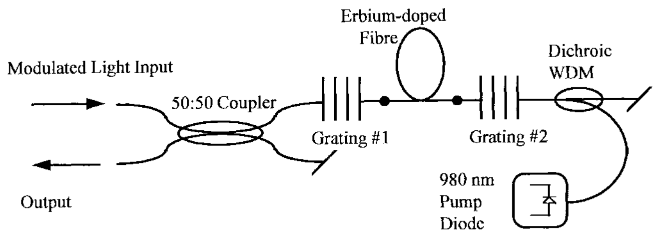


Fig. 1. Optical tapped-delay-line microwave signal processor.

between the gratings. Half the light is reflected off grating #1, and half is transmitted and then passed through the erbium doped amplifier which provides gain, before fully reflecting off grating #2. Upon reflection from this grating, the signal follows a return path through the active fiber and encounters grating #1 again. This grating couples approximately half the signal to the output, which forms a tap output element of the impulse response, while returning some of the signal to be re-amplified and to repeat the process. Hence, the signal is reflected successively from the gratings by passing it back and forth between the gratings and the active fiber. The active fiber is used to compensate for the light coupled out and for other losses, and the total gain is limited to 2. This configuration has the ability to produce a very large number of taps, and also has the advantage that the signal always traverses the same path length, thus ensuring that the tapped-delay-time spacing and weights are uniform because the reflections are all obtained from the same gratings.

The output of this discrete-time signal processor is given by

$$y(t) = \sum_{n=0}^{N-1} W_n x(t - \tau_s n) \tag{1}$$

where $W_n$ is the value of the $n$th tap weight, $N$ is the number of taps, and $\tau_s$ is the sampling period. A large number of taps, $N$, is required to achieve high resolution in the frequency domain, and a short delay time $\tau_s$ or high sampling frequency is required to achieve high resolution in the time domain. This structure can achieve a large number of taps and, hence, can obtain a very narrow bandpass frequency response.

The impulse response of the processor consists of a slowly decaying series of pulses. The filter bandpass is inversely proportional to the number of taps. Hence, the loss per iteration is important in determining the sharpness of the frequency response. The fractional value of the $i$th impulse response element relative to the first impulse response is given by

$$P_i/P_o = (1 - r_1)^2 g^{2(i-1)} r_1^{i-3} r_2^{i-1} \tag{2}$$

where $r_1$ is the reflectivity of grating 1, $r_2$ is the reflectivity of grating 2, and $g$ is the single pass gain of the erbium-doped fiber amplifier. By controlling the gain of the active medium, the effective number of taps can be controlled, and hence, the bandwidth of the filter response can be tuned.

## III. Results

Optical-fiber Bragg gratings with a center wavelength of 1558 nm, and reflection bandwidth of 0.5 nm, were used in the linear active filter of Fig. 1. The gratings were fabricated using the UV exposure technique in photosensitive germanosilicate fiber, and were fusion spliced to the active-fiber section. Measurements showed that the gratings had reflectivities of 53% and 98.5% at the operating wavelength of the laser source. A Fabry–Perot laser diode was modulated and used as the light source for the system. Since only a low-single-pass gain of <1.4 is required in this structure, a short length of highly doped erbium-aluminosilicate fiber was employed to provide the necessary gain. Here, a 40-cm length of 1000-parts-per-million (ppm) erbium-doped fiber was used to test the operation of the active transversal filter; however, this was not optimized, and it is possible to use shorter lengths than this with higher doped fiber to obtain smaller delays. The gain of the active fiber in the filter could be tuned by controlling the pump power.

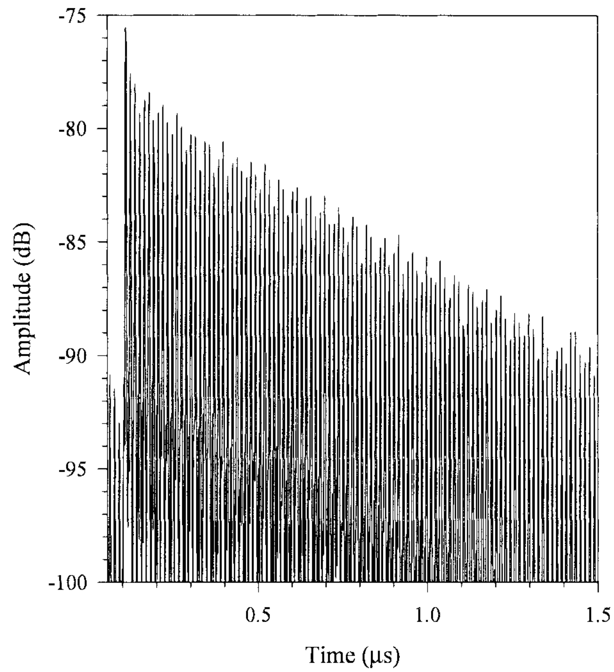


Fig. 2. Measured impulse response of the delay-line filter.

The measured time-domain impulse response of the active grating based filter, as displayed on a network analyzer, is shown in Fig. 2. This shows the large number of taps (in excess of 270) that can be generated using this technique. Since the gain of the active section needs to be slightly less than the value for lasing, the response shows a slowly decaying series of impulses. The tap spacing is entirely regular since it corresponds to the delay time between the gratings, which is the same for all elements of the impulse response. The taper rate of the impulse response for a particular gain condition is shown in Fig. 3. The predicted response has been obtained using (2), and a characterization of the erbium-doped amplifier-gain parameters and the grating reflectivities. Comparison between the measured and predicted characteristics shows excellent agreement.

The frequency response of the filter, measured on the network analyzer, is shown in Fig. 4. This response exhibits a quality factor $(Q)$, defined as the ratio as the center frequency of the first-order response to the 3-dB filter bandwidth, of 325.

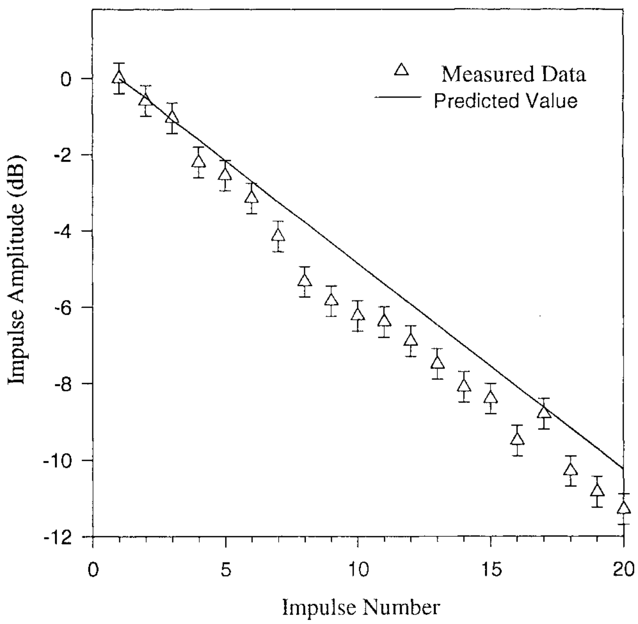


Fig. 3. Predicted and measured taper rate of the impulse response.

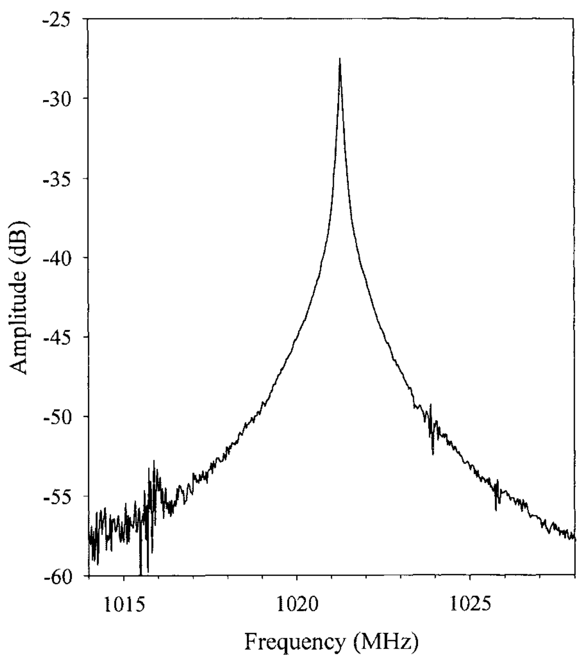


Fig. 4. Measured frequency response of the optical delay-line filter.

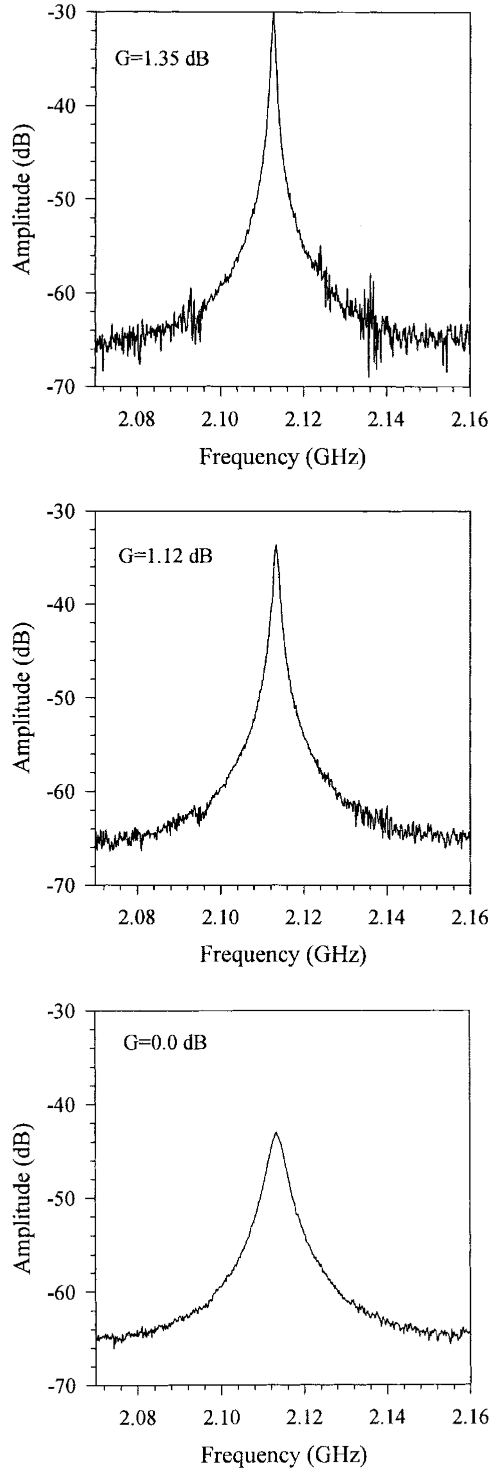


Fig. 5. The frequency response of the tapped-delay-line bandpass filter for decreasing values of gain and pump power of the active fiber.

To the authors' knowledge, this is the highest reported $Q$ for an optical-transversal delay-line filter.

Measurements on the frequency response of this filter showed precise regularity in the bandpass response to at least 20 GHz (which was the limit of the measurement system). This is due to the regularity of the tap spacing, which is a direct result of the fact that the signal always traverses the same path length, since the reflections are all obtained from the same gratings. This means that the filter can be used well into the millimeter-wave range. This is an important advantage over previous approaches for tapped-delay-line filters, which used different elements for each tap. For these latter approaches, even small irregularities (which are inevitable) in the path lengths and delays for the many taps required for a bandpass filter, results in a blurring of the frequency response at high frequencies, and limits their use at the higher microwave and millimeter-wave frequencies.

Furthermore, it can be noted that this processor topology has the capability for tuning. The filter passband width can be tuned simply by controlling the gain of the active fiber.

The effective number of taps produced, and hence, the $Q$ of the filter, depends on the gain of the active region. This also controls the proximity of the pole in the $z$-plane to the unit circle, and hence, the sharpness of the frequency response of the discrete-time signal processor. The frequency response of the tapped-delay-line bandpass filter for various values of gain and pump power in the active fiber is shown in Fig. 5. At lower levels of fiber amplifier gain, the taper in the impulse response train decays faster, producing fewer taps in the impulse response, and consequently, the $Q$ decreases and the filter bandwidth increases.

Finally, it can be noted that this processor topology also has the ability to be extended to tunable frequency operation by using wavelength selective-chirped fiber Bragg gratings [11] as the tapping elements. The use of long-chirped fiber Bragg gratings, together with wavelength control of the optical source over the chirp range of the grating, enables the point of reflection within the grating to be shifted. Hence, the delay time $\tau_s$ in (1) of the discrete-time signal processor can be varied. This provides the ability to obtain a continuously variable, and widely tunable, narrow-band processor.

## IV. Conclusion

A new active photonic signal processor, which achieves a high-$Q$ microwave bandpass frequency response, has been presented. It comprises only two fiber Bragg-grating sampling elements together with a section of active fiber, yet is capable of producing a very large number of taps with precise delay characteristics, and results in a very narrow-band filter response. Moreover, the structure has the advantage that the signal always traverses the same path length, thus ensuring that the tap-delay-time spacing and weights are uniform since the reflections are all obtained from the same gratings. This has enabled the realization of high-$Q$ microwave bandpass filters. The impulse response of the filter demonstrates well in excess of 270 taps, with regular spaced time delays between them. The filter has demonstrated a $Q$ of 325, which to the authors' knowledge is the highest reported $Q$ for an optical-transversal delay-line filter. The filter operation extends to millimeter-wave frequencies. The structure is simple, and can also be implemented in planar lightwave circuit technology. Furthermore, this processor topology has the capability for achieving tunable operation. The filter passband width can be tuned simply by controlling the gain of the active fiber. In addition, the filter frequency can be tuned by using wavelength selective-chirped fiber Bragg gratings as the tapping elements. This offers high-resolution microwave optical signal processing with high time-bandwidth operation.

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