Jammed-array wideband sawtooth filter

Zhongwei Tan,1,2 Chao Wang,2 Keisuke Goda,2,3,4,* Omer Malik,2 and Bahram Jalali2,3,4,5

1Institute of Lightwave Technology, Key Lab of All Optical Network & Advanced Telecommunication Network of EMC, Beijing Jiaotong University, Beijing 100044, China
2Electrical Engineering Department, University of California, Los Angeles, CA 90095, USA
3California NanoSystems Institute, Los Angeles, CA 90095, USA
4Department of Bioengineering, University of California, Los Angeles, CA 90095, USA
5Department of Surgery, David Geffen School of Medicine, University of California, Los Angeles, CA 90095, USA

goda@ee.ucla.edu

Abstract: We present an all-optical passive low-cost spectral filter that exhibits a high-resolution periodic sawtooth spectral pattern without the need for active optoelectronic components. The principle of the filter is the partial masking of a phased array of virtual light sources with multiply jammed diffraction orders. We utilize the filter’s periodic linear map between frequency and intensity to demonstrate fast sensitive interrogation of fiber Bragg grating sensor arrays and ultrahigh-frequency electrical sawtooth waveform generation.

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References and links
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1. Introduction

Technological advances in fabrication of high-quality optical elements for the past few decades have enabled the widespread use of low-cost optical filters [1]. Currently, various types of optical filters are commercially available, such as neutral density filters, dichroic filters, and band-pass filters, for numerous applications including optical communications, astronomy, defense, remote sensing, and biomedical imaging [1]. The performance in many of these systems is intimately tied to the capabilities of optical filters.
Optical filters with complex spectral response are useful for a broad range of applications such as spectroscopy, pulse shaping, waveform generation, fiber Bragg grating (FBG) sensors, and optical communication systems. For example, a periodic sawtooth filter is important as it can serve as an edge filter array for fast sensitive interrogation of a FBG sensor array and multi-channel wavelength monitoring in dense wavelength-division multiplexing (WDM) optical communication systems [2]. Unfortunately, such complex filters are difficult to build with passive optical components due to limitations of fabrication technology that prohibit design of required parameters. While efforts have been made to produce sawtooth spectral response, previously reported methods [3, 4] fall short of the requirements for large bandwidth, periodicity, high duty cycle, and linearity. Alternatively, the periodic sawtooth filter response can be achieved by using active optoelectronic components such as a spatial light modulator sandwiched between a pair of diffraction grating [5], but their costs are typically high, limiting practical use.

In this paper, we propose and demonstrate a simple all-optical passive low-cost spectral filter that exhibits a high-resolution periodic sawtooth spectral pattern without the need for active optoelectronic components. The filter builds on an integration of a virtually-imaged phased array (VIPA) [6–8] and intensity mask along with two lenses and hence consists of totally passive optical components with a low cost. Designed to be a side-entrance Fabry-Perot etalon with a carefully tuned angle of incidence, the VIPA behaves as a spatial disperser (analogous to a prism or diffraction grating) yet with multiple diffraction orders that overlap with each other. In other words, the VIPA produces a phased array of virtual light sources that consists of multiply “jaammed” diffraction orders of wideband light. Consequently, when the phased array is partially masked, a high-resolution periodic sawtooth-shaped spectrum or a series of linearly sloping edges is produced. To show the utility of the filter, we demonstrate its application to fast sensitive interrogation of FBG sensor arrays and ultrahigh-frequency electrical sawtooth waveform generation.

2. Jammed-array wideband sawtooth (JAWS) filter

The concept of the filter which we refer to ask the jammed-array wideband sawtooth (JAWS) filter is depicted in Fig. 1. The primary components of the filter are the VIPA and intensity mask. As shown in Fig. 1a, a collimated broadband light is focused with a cylindrical lens into the VIPA. The returned light exhibits a periodic sawtooth spectral pattern. In other words, the VIPA produces a phased array of virtual light sources that consists of multiply “jaammed” diffraction orders of wideband light. Consequently, when the phased array is partially masked, a high-resolution periodic sawtooth-shaped spectrum or a series of linearly sloping edges is produced. To show the utility of the filter, we demonstrate its application to fast sensitive interrogation of FBG sensor arrays and ultrahigh-frequency electrical sawtooth waveform generation.

Fig. 1. JAWS filter. (a) Schematic. The dispersed light with spatially overlapped degenerate FSRs interferes in the Fourier plane at the intensity mask. The returned light exhibits a periodic sawtooth spectral pattern. (b) Simulation of the mapping relation between the wavelength and diffraction angle. (c) Simulation of the filter response: when the area of x < 0 is masked (top) and when the area of x > 0 is masked (bottom).
the VIPA. Here the incident beam is focused on the back surface of the VIPA. The dispersed light interferes at the intensity mask by another cylindrical lens which acts as a Fourier lens. As shown in Fig. 1b, different wavelength components of the beam are diffracted at different angles with multiple diffraction orders and hence mapped onto different transverse displacements in the Fourier plane. The role of the intensity mask is to partially block the phased array while allowing reflection of the unblocked portion of the beam back to the VIPA. The filter operation can be intuitively understood by recognizing that the intensity gradient in the Fourier plane exhibits a monotonous decrease as the diffraction angle increases both positively and negatively, rendering the partial masking of the intensity map equivalent to the additive synthesis of the infinite Fourier series. Consequently, the filter exhibits a periodic sawtooth response pattern with a series of either positive or negative slopes (Fig. 1c).

2.1 Theory

The spectral response of the JAWS filter can be computed analytically. Using the modified spatial Fourier transform by the Fourier lens (assuming it is a thin lens) obtained through a Fresnel diffraction analysis, the intensity distribution function in the plane of the intensity mask is given by [6]

$$I(x, \omega) = \exp \left( - \frac{2f_1^2 x^2}{a^2} \right) \frac{1}{\left( 1 - R_1 R_2 \right)^2 + 4R_1 R_2 \sin^2 \left( \omega / 2 \text{FSR} \right)}$$

where $\text{FSR} = c / (2d \cos \theta_1) \cdot \text{sin} \theta_1 (\cos \theta_1 / f_2^2 + \text{sin} \theta_1 / f_2^2)$ is the free spectral range (FSR) of the VIPA, $f_1$ is the focal length of the cylindrical lens before the VIPA, $f_2$ is the focal length of the Fourier lens, $\theta_1$ is the incident angle of the beam with respect to the VIPA, $R_1$ and $R_2$ are the reflectivity of the front and back surfaces of the VIPA, $a$ is the radius of the collimated beam prior to the cylindrical lens, $d$ is the thickness of the VIPA, $a$ is the angular frequency, and $x$ is the transverse displacement of the beam with respect to the position of the center wavelength in the plane of the intensity mask. Equation (1) is a Lorentzian function with resonance peaks when the following resonance conditions are satisfied:

$$\omega / 2 \text{FSR} = m \pi \quad \text{for} \quad m = 0, \pm 1, \pm 2, \ldots$$

If the lower part of the intensity mask ($x < 0$) is covered so that only the upper part ($x > 0$) is reflected back to the VIPA, the transfer function of the filter for the frequency within the range of one FSR is given by

$$T(x > 0, \omega) = \int_{0}^{x} I(x, \omega) dx \propto \sum_{m=0}^{\infty} \exp \left[ - \frac{2f_1^2 x^2}{a^2} \left( \frac{1}{\tan \theta_1} \frac{m \pi c}{d \omega \text{sin} \theta_1} \right)^2 \right] \propto - \frac{da}{cf_1} \omega,$$  

where we have only considered the dominant intensities at the resonance frequencies, used the approximate linear relation between $x$ and $\omega$ from Eq. (2), assuming $xf_2^2 \ll 1$ and computed the summation by replacing it with an integral. Equation (3) repeats itself at every FSR, producing a periodic sawtooth spectral pattern with negative slopes (in the frequency domain while the sign is opposite in the wavelength domain) as shown in Fig. 1c. Likewise, if the upper part of the intensity mask ($x > 0$) is covered, the transfer function of the filter for the frequency within the range of one FSR is given by $T(x < 0, \omega) \propto (dalcf_1/\omega)$, which gives a periodic sawtooth spectral pattern with positive slopes (in the frequency domain while the sign is opposite in the wavelength domain) as shown in Fig. 1c.

2.2 Experimental demonstration

To demonstrate the JAWS filter, we constructed the apparatus shown in Fig. 1a. The performance of the filter can be estimated from the parameters of its optical components: $d = 2.4$ mm, $f_1 = 100$ mm, $f_2 = 150$ mm, $\theta_1 = 4^\circ$, $R_1 = 99.5\%$, $R_2 = 95\%$, and $a = 1.2$ mm. The
measured filter response (transfer function) is shown in Fig. 2, indicating that the experimental results are in good agreement with the aforementioned theoretical analysis. Broadband sawtooth filtration for more than 30 nm was achieved. The tooth size (bandwidth) and FSR are measured to be 0.4 nm and 0.5 nm, respectively, and hence the duty cycle of the sawtooth pattern is 80%. These parameters can easily be optimized by varying the thickness of the VIPA, depending on the requirements for various applications. While the optical loss in the filter is relatively large (~20 dB) due to aberrations in the free-space optics and inherent loss in the VIPA, it can easily be compensated by an optical amplifier such as an erbium-doped fiber amplifier (EDFA).

3. Utility of the JAWS filter

To show the utility of the JAWS filter, we used it to demonstrate two applications: (1) fast sensitive interrogation of a FBG sensor array, and (2) ultrahigh-frequency electrical sawtooth waveform generation. In the following sections, we discuss our experimental demonstration of the applications.

3.1 Application to fiber Bragg grating sensors

The ability to read out variations in strain or temperature with high sensitivity at high speed and low cost is desirable for FBG sensors [9]. Unfortunately, these requirements are difficult to satisfy simultaneously with conventional FBG sensor interrogation systems in which the demodulation of strain-induced wavelength shifts is typically limited by wavelength scanning devices, analog-to-digital converters, or digital processors [10]. With an edge filter, the wavelength shift can be converted into an intensity change in the reflected light from the FBG sensor, but there is a trade-off between measurement resolution and dynamic range when using a broadband edge filter [2, 10], limiting the number of FBG sensors in a FBG sensor array system. Our JAWS filter overcomes these limitations and provides the capability of all-optical linear conversion of strain-induced wavelength shifts in multiple FBGs into intensity changes. As a result, it enables fast sensitive interrogation of FBG sensor arrays.

The FBG sensor array with the JAWS filter is schematically shown in Fig. 3a. A broadband pulse train with a pulse width of 2 ns at a pulse repetition rate of 25 MHz was generated by modulating an amplified spontaneous emission (ASE) source with an intensity modulator and was used as an optical source for the FBG sensor. Here we used three FBGs with center wavelengths of 1541.1 nm, 1541.6 nm, and 1542.2 nm. The reflected pulses from the FBGs are directed via an optical circulator and EDFA toward the JAWS filter, which

Fig. 2. Experimental demonstration of the JAWS filter. The period of the sawtooth spectrum (i.e., the FSR) can easily be varied by changing the thickness of the VIPA, depending on the requirements for various applications. The slight nonlinearity in the sawtooth pattern comes mainly from the finite length of the VIPA due to which a small portion of the resonant light leaks out of the top end of the VIPA and can be suppressed by the use of a longer VIPA.
converts the wavelength shift into a change in the intensity of the pulse. The filter output is then detected by a high-speed photodiode.

The performance of the FBG sensor is shown in Fig. 3b. The figure indicates that the wavelength shift due to an applied strain force on each FBG was converted to an intensity change in each pulse. Here weak and strong strain forces were applied to stretch the second and third FBGs, respectively, while no strain force was applied to the first FBG. The result is compared with the wavelength shifts directly measured by an optical spectrum analyzer (Fig. 3c), indicating our simultaneous demodulation of three FBG sensors with the JAWS filter. Furthermore, we obtained the relation between the strain and intensity change for each FBG (Fig. 3d). The figure indicates that the mapping relation is linear for every channel. The demodulation speed and sensitivity of the FBG sensor integration were found to be 25 MHz and 0.05 dB/pm. The number of channels can easily be increased by adding more FBGs to the sensor, covering the entire C band without major modifications.

FIG. 3. Application of the JAWS filter to a FBG sensor array. (a) Experimental apparatus. Strain-induced wavelength shifts in the reflections from the FBGs are converted by the JAWS filter into intensity changes. (b) Pulses detected by the photodiode with and without strain on the FBGs, indicating that the applied strain is converted to the intensity change in each pulse. (c) Corresponding spectra of the pulses reflected by the FBGs measured by an optical spectrum analyzer, showing that the intensity change agrees with the wavelength shift for each pulse. (d) Relation between intensity change and strain on each FBG, indicating that all the FBGs have linear relations.

3.2 Application to ultrahigh-frequency sawtooth waveform generation

The ability to produce broadband sawtooth waveforms is essential as it is a fundamental requirement for wideband communications, diagnostic instrumentation, and high-speed signal processing [11]. While the generation of such waveforms is hindered by the limited bandwidth and dynamic range of digital-to-analog conversion technology, our filter combined with dispersive Fourier transformation [12] can circumvent the limitation and hence produce such waveforms since it does not require electronic switching or transistor circuitry. Dispersive Fourier transformation is an optical method that maps the spectrum of a broadband pulse into a temporal waveform using group-velocity dispersion (GVD) [12].

The sawtooth waveform generator with the JAWS filter is schematically shown in Fig. 4a. The optical source is a femtosecond fiber laser with a center wavelength of 1540 nm. After supercontinuum generation and band-pass filtration, a pulse train with a flat spectrum of 20 nm bandwidth is generated and enters the sawtooth spectral filter. The spectrum of the filter output is mapped into a time-domain waveform by \(-1320\) ps/nm GVD in the dispersive fiber.
The generated sawtooth waveform is shown in Fig. 4b. The waveform was measured by an oscilloscope with 16 GHz bandwidth and 50 GS/s sampling rate. The figure indicates that the generated sawtooth waveform has a fundamental frequency of 1.52 GHz, which typically requires larger bandwidth than 30 GHz (20th harmonic). The generation of such a high-frequency sawtooth waveform is usually difficult with electronic circuits. It is worthwhile to note that there is no fundamental limit on the frequency of the sawtooth waveform that the JAWS filter can offer. With a smaller GVD, a sawtooth waveform with a higher fundamental frequency can easily be achieved. In practice, detection of such a high-frequency is difficult since detection systems with more than 20 GHz bandwidth are required.

Fig. 4. Application of the JAWS filter to ultrahigh-frequency sawtooth waveform generation. (a) Experimental apparatus. The spectrum filtered by the JAWS filter is mapped into the time domain by GVD in the dispersive fiber. (b) Sawtooth waveform produced by the sawtooth generator and measured by an oscilloscope with 16 GHz bandwidth and 50 GS/s sampling rate. The fundamental frequency of the sawtooth waveform is 1.52 GHz.

4. Summary

We have proposed and demonstrated a simple all-optical passive low-cost spectral filter that produces a periodic sawtooth transfer function without the need for active optoelectronic components. To show the filter’s utility, we have demonstrated two potential applications of the filter.

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