All-optical temporal differentiator based on a single phase-shifted fiber Bragg grating

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Abstract: We propose and demonstrate an all-optical temporal differentiator based on a single π-phase-shifted fiber Bragg grating operated in reflection. This device can efficiently process arbitrary optical temporal waveforms with bandwidths up to a few gigahertz.

1. Introduction

All-optical temporal differentiators are of general interest as basic building blocks in ultrahigh-speed optical signal processing circuits in exact analogy with their electronic counterparts. More specifically, all-optical differentiators could be used for optical pulse shaping, and optical control and sensing. As they can alleviate the bandwidth limitations typical of electronic solutions, they are also attractive for realizing specific signal processing operations over ultra-wideband microwave signals (by first transferring the microwave signal into the optical domain using e.g. electro-optic modulation). Very recently, it has been shown theoretically [1] that a single uniform long-period fiber grating (LPG) can operate as a temporal differentiator over optical signals with sub-picosecond temporal features. Based on this finding, LPG-based optical differentiators capable of processing signals with temporal features as fast as ≈ 180 fs have been fabricated and experimentally tested [2]. The LPG-based solution is of specific interest for differentiating optical waveforms with bandwidths > 1THz. However this previous solution is not suitable (e.g. it is very energetically inefficient) for processing optical signals with bandwidths in the GHz regime. In this letter, we propose and experimentally demonstrate a new all-optical differentiation approach, which is specially suited for operation on arbitrary optical signals with bandwidths up to a few GHz. Specifically, we demonstrate that a single π phase shifted fiber Bragg grating (FBG) operated in reflection can accurately calculate the first time derivative of the complex field (amplitude and phase) of a GHz-bandwidth input optical waveform.

2. Principle

The temporal operation of a first-order optical differentiator can be mathematically described as $v(t) \propto \partial u(t)/\partial t$, where $u(t)$ and $v(t)$ are the temporal optical waveforms (complex envelopes) at the input and at the output of the system, respectively, and t is the time variable. In the spectral domain, $V(\omega) \propto -j\omega U(\omega)$, where $U(\omega)$ and $V(\omega)$ are the Fourier transform of $u(t)$ and $v(t)$, respectively and ω is the base-band frequency ($\omega = \omega_{opt} - \omega_0$, where ω_{opt} is the optical frequency and ω_0 is the carrier frequency). Thus, first-order optical differentiation can be implemented using an optical filter with a transfer function that varies linearly on frequency, $H(\omega) \propto -j\omega$. A key feature of a first-order optical differentiator is that it must introduce a π phase shift exactly at the signal's central frequency, ω_0. We have found out that these required spectral characteristics are provided by a phase-shifted FBG consisting of two concatenated identical uniform FBGs with a π phase shift between them. Specifically, this FBG device provides the required spectral features for optical differentiation within a narrow bandwidth (up to a few GHz) around the transmitted resonance wavelength (reflection dip). In principle, in order to achieve the required exact π phase shift at the signal's central frequency the FBG structure must exhibit an ideal π phase shift and the two concatenated uniform gratings must be identical (these features would ensure an exact null at the FBG transmission resonance frequency). In practice, our numerical simulations show that a resonance deep > 30dB is sufficient to ensure a deviation error < 2% in the differentiation process of an optical signal with a sufficiently narrow bandwidth).

3. FBG fabrication and characterization

A π phase-shifted Bragg grating was fabricated using the UV radiation of a cw frequency doubled Ar-ion laser with power of about 160 mW. The UV beam was focused by a cylindrical lens trough a 1 mm slit and a phase mask (period of 1065 nm) onto the core of a hydrogen-loaded germano-silicate fiber. The written phase-shifted grating consists of two consecutive uniform FBGs, each 1-mm long. A π-phase shift between these two uniform gratings was produced by accurately shifting the mask relative to the fiber using a piezoelectric actuator following the photoinscription of the first

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grating. The spectral reflectivity of the fabricated FBG structure was measured by a tunable semiconductor laser (Ando AQ4321D) and an optical spectrum analyzer (Ando AQ6317B) with a wavelength resolution of 1 pm. The measured spectrum around the grating reflection dip is shown in the inset of Fig.2(a). The measured depth of this reflection dip is -34.5 dB, which should be sufficient for optical differentiation, according to our simulations. The 3-dB bandwidth of the dip is 0.17 nm and we estimate that optical signals with bandwidths up to ≈ 5 GHz can be accurately differentiated with this device (this is the bandwidth over which the reflection amplitude in the dip exhibits a linear variation). The grating spectral phase was measured using the method reported in Ref. [3] and the result of this measurement is shown in the inset of Fig. 2(b). As anticipated, the measured π phase jump is abrupt enough to accurately implement optical differentiation.

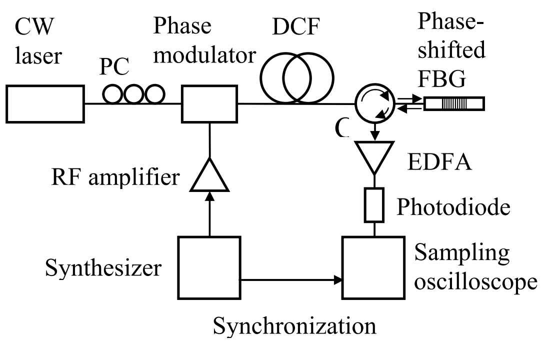

Fig. 1. Experimental setup

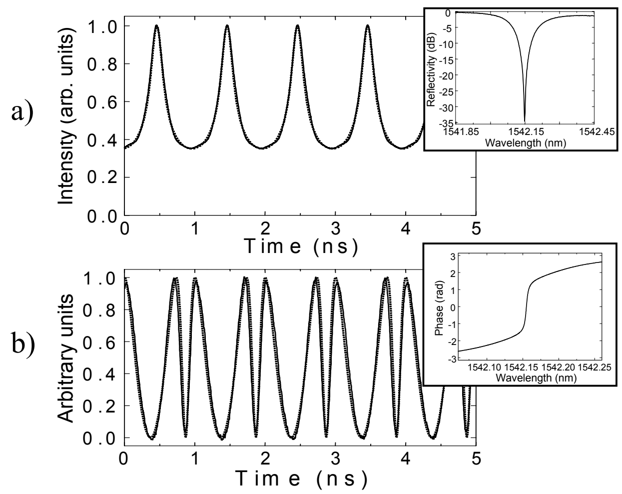

Fig. 2. Experimental results (solid curves) and theoretical predictions (dotted curves): Input (a) and output (b) signals in the FBG differentiator. The insets show the measured FBG spectral characteristics.

4. Experimental results

The operation of the fabricated phase-shifted fiber Bragg grating as an optical differentiator was tested using the experimental setup shown in Fig. 1. As an optical source, we used the same tunable semiconductor laser as for the grating spectrum measurement. The CW radiation of the laser was sinusoidally modulated by a $LiNbO_3$ electro-optic (EO) phase modulator driven by an RF sinusoid from an RF synthesizer and RF amplifier. In the experiment presented here, the input optical pulses were created by propagating the sinusoidally phase modulated light through a span of dispersion compensating fiber (DCF) with a total dispersion of −4074 ps/nm. These pulses were reflected from the FBG-based optical differentiator and directed by a circulator to a photodiode and an oscilloscope with a bandwidth of 50 GHz. Fig. 2(a) (solid curve) shows the pulses formed after propagation through DCF dispersion for a RF modulation frequency f_m = 1 GHz and a modulation index in the EO modulator of A = 2.405 rad. For comparison, we also show in fig. 2(a) (dotted curve) the numerically calculated pulses assuming the same parameters as in the experiment. The repetition rate of the generated optical pulse train is fixed by the modulation frequency to 1GHz. The results of optical differentiation of the input pulses in Fig. 2(a) after reflection in the phase-shifted FBG structure are shown in Fig. 2(b) (solid curves for experimental results and dotted curves for an ideal differentiation process). The agreement between theory and experiments is remarkable (average deviation between theoretical and experimental curves < 7%).

It should be noted that the demonstrated optical differentiator provides the derivative of the complex pulse field (including amplitude and phase). In another set of experiments, the optical differentiator was used for phase-to-intensity conversion of a sinusoidally phase modulated signal, demonstrating again an excellent agreement between theory and experiments.

5. Conclusions

A very simple and efficient all-optical (all-fiber) first-order temporal differentiation technique based on the use of a single phase-shifted FBG has been proposed and experimentally demonstrated. This device calculates the first temporal derivative of the complex envelope (amplitude and phase) of arbitrary optical waveforms with bandwidths up to a few gigahertz. This development should prove very useful for all-optical information processing or for implementing specific signal processing tasks over ultra-wideband microwave waveforms.

References

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