Integrated Temporal Fourier Transformer Based on Chirped Bragg Grating Waveguides

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Abstract:
We experimentally realized an integrated temporal Fourier transformer based on a linearly-chirped Bragg grating waveguide written in silica glass with a femtosecond laser. The device operates in reflection and has a 10-nm bandwidth.

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All-optical time-domain pulse processing and shaping devices are of great importance for a wide range of applications in different fields, including ultra-fast information processing and computing, nonlinear optics, biomedical imaging, ultrahigh-speed optical telecommunications, and many others. A variety of fundamental optical pulse processing techniques have been developed in free space [1], as well as in fibers (by means of fiber Bragg [2] and long-period [3] gratings). Integrating the existing pulse processing techniques on an optical chip is important for the development of integrated optical circuits capable of performing a full set of functions for all-optical signal processing.

Concerning this latest aspect, it has been theoretically demonstrated [4] and experimentally verified [2] that a linearly-chirped fiber Bragg grating operated in reflection is capable of performing a temporal Fourier transform of an incident optical pulse. By temporal (or real-time) Fourier transform here we understand the mapping of the energy spectrum of the input optical pulse (signal under test) along the time axis, *i.e.*, frequency-to-time mapping. This effect is based on the analogy between the paraxial diffraction in space and first-order chromatic dispersion of optical pulses. The spectral response of a linearly-chirped Bragg grating over its reflectivity bandwidth can be expressed as $H(\omega) = |H(\omega)| \exp[\mathrm{i}\Phi(\omega)]$, and its corresponding temporal impulse response can be represented as $h(t) \propto \exp[\mathrm{i}\pi/(2\ddot{\Phi})t^2]$, which is mathematically identical to the amplitude response of a free-space propagation system under Fresnel conditions. The grating's reflectivity is given by $R(\omega) = |H(\omega)|^2$, and the first-order dispersion coefficient is the second derivative of the phase with respect to the angular frequency: $\ddot{\Phi} = \partial^2\Phi/\partial\omega^2$. A linearly-chirped Bragg grating can perform a temporal Fourier transform of an optical pulse, extending over a time duration Δt_0, if it has a sufficient amount of dispersion, such that $|\ddot{\Phi}| \gg \Delta t_0^2/2\pi$, which is usually referred to as the temporal Fraunhofer condition [4]. The spectral bandwidth of the optical pulse under test should also be limited to the grating reflectivity bandwidth.

In this report, we experimentally realize, for the first time to our knowledge, an integrated temporal Fourier transformer. Our device is based on a linearly-chirped Bragg grating written in silica glass with a femtosecond laser [5]. This novel material platform is fiber-compatible and has a mode size and shape similar to that of a single-mode fiber, which makes it especially attractive for integrated optical devices. Our grating is 5-cm-long and has a reflectivity bandwidth of 10 nm, being capable of Fourier transforming ultra-fast optical signals with durations exceeding 20 ps.

The experimental setup used to demonstrate the temporal Fourier transform function of our device is shown in Fig. 1. As a source of the incident radiation, we used a wavelength-tunable (C-band) passively-mode-locked fiber laser (FFL-20 from *Pritel Inc.*) generating nearly transform-limited Gaussian pulses at a repetition rate of 16.7 MHz. The internal fiber cavity had a switchable optical band-pass filter (OBPF). In our experiment we used Gaussian-shaped OBPFs with 3-nm and 5-nm bandwidths. We split the laser pulse train into two arms with a 3-dB beam splitter. In the first arm, the beam passed through a split-and-delay stage in fiber to produce the input signal under test, consisting of two 7.6-ps-spaced pulses. To change the

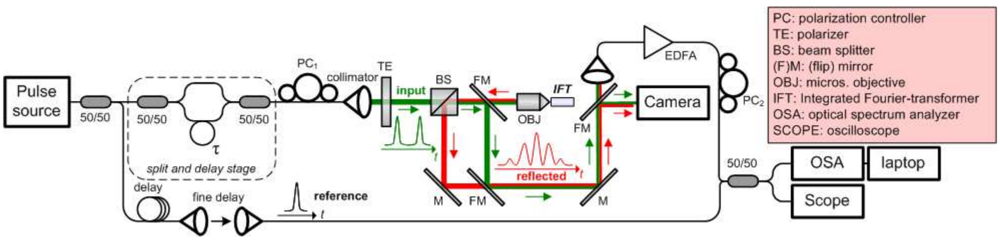

FIG. 1: Experimental setup.

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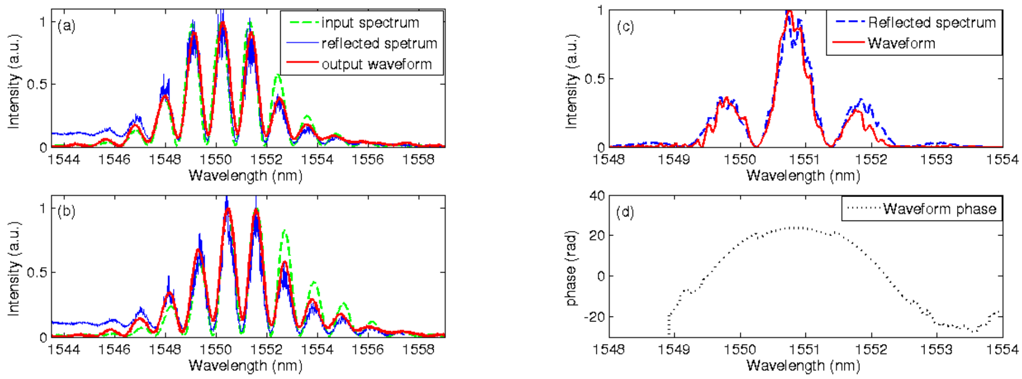

FIG. 2: Incident (green) and reflected (blue) spectra superimposed on scaled oscilloscope traces of the output temporal waveforms (red): (a) for the in-phase incident pulses, (b) for the out-of-phase incident pulses. The data were obtained with a 5-nm OBPF filter in the laser cavity. (c) The spectrum (blue) and the scaled temporal waveform (red) of the reflected signal reconstructed through FTSI, obtained with a 3-nm OBPF. (d) The phase of the reflected signal reconstructed through FTSI.

relative phase between the two pulses, we slightly detuned the laser pulse central wavelength. This way we were able to obtain both in-phase and π-phase-shifted pairs of pulses. The signal from the second arm was used as a reference beam in the Fourier Transform Spectral Interferometry (FTSI) [6] setup used to recover the temporal intensity and phase profiles of the reflected optical pulse. The double-pulse signal was sent to a bulk-optics setup through an input collimator. We coupled the signal to the integrated Bragg grating by a 10× microscopic objective, and, after amplification, it was recombined with the reference beam so as to produce spectral interference. The reference beam was delayed with respect to the reflected signal by 30 − 40 ps to match the resolution of the optical spectrum analyzer (OSA) used to acquire the interference pattern. In addition, the temporal intensity profile of the output temporal waveform was captured using a fast sampling oscilloscope with a photodiode with 12-ps rise time.

In Fig. 2, we show the experimental performance of the temporal Fourier transformer. Figs. 2(a) and 2(b) display the spectra of the incident and reflected signals together with the scaled oscilloscope traces of the temporal reflected signals for the cases when the two incident pulses were in-phase and out-of-phase, respectively. The results shown in Figs. 2(a) and 2(b) were obtained using a 5-nm filter in the fiber laser source cavity. Notice that the measured spectral bandwidths correspond to transform-limited pulses with a time duration of 700 fs (FWHM). The similarity between the output temporal waveform and the incident spectrum confirms that the device operates as a temporal Fourier transformer. The slight discrepancy is due to the ramp in the grating reflectivity spectrum, mainly caused by the propagation losses and reflectivity ripples. In Fig. 2(c), we show the spectrum of the reflected signal together with its scaled temporal waveform trace for a pair of in-phase incident pulses, as reconstructed through FTSI for the case when the laser operated with a 3-nm filter in the cavity. The phase of the reflected signal reconstructed through FTSI is shown in Fig. 2(d). Using these data, we found the dispersion coefficient of the grating to be $\ddot{\Phi} = 34.8$ ps/nm, which satisfies the temporal Fraunhofer condition for signals as long as 20 ps. This dispersion coefficient value was indeed used for scaling the temporal waveforms in Figs 2(a)-2(c) along the wavelength axis. The data in Fig. 2 present a solid evidence of the device operation as a temporal Fourier transformer of signals in the sub-picosecond to picosecond ranges.

In conclusion, we have experimentally demonstrated the performance of an integrated chirped Bragg grating with a 10-nm bandwidth written in silica with a femtosecond laser as a temporal Fourier transformer of (sub-)picosecond optical pulses. This experiment represents a very promising first step towards the realization of ultra-fast pulse processing devices in this new material platform.

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[1] A. M. Weiner, “Femtosecond optical pulse shaping and processing,” Prog. Quantum Electron. **19**, 161–237 (1995).
[2] J. Azaña, L. R. Chen, M. A. Muriel, and P. W. E. Smith, “Experimental demonstration of real-time Fourier transformation using linearly-chirped fibre Bragg grating,” Electron. Lett. **35**, 2223–2224 (1999).
[3] J. Azaña, “Ultrafast analog all-optical signal processors based on fiber-grating devices,” IEEE Photonics J. **2**, 359–386 (2010).
[4] M. A. Muriel, J. Azaña, and A. Carballar, “Real-time Fourier transformer based on fiber gratings,” Opt. Lett. **24**, 1–3 (1999).
[5] H. Zhang and P. R. Herman, “Chirped Bragg grating waveguides directly written inside fused silica glass with an externally modulated ultrashort fiber laser,” IEEE Photon. Technol. Lett. **21**, 277–279 (2009).
[6] L. Lepetit, G. Cheriaux, and M. Joffre, “Linear techniques of phase measurement by femtosecond spectral interferometry for applications in spectroscopy,” J. Opt. Soc. Am. B **12**, 2467–2474 (1995).