Long-period-fiber-grating-based filter configuration enabling arbitrary linear filtering characteristics

Radan Slavík,[1,2,*] Mykola Kulishov,[3] Y. Park,[4] and J. Azaña[4]

[1]*Institute of Photonics and Electronics AS CR, Chaberská 57, Prague, 182 51, Czech Republic*
[2]*Also with Czech National Research and Education Network, a.l.e., Zikova 6, Prague, 166 27, Czech Republic*
[3]*HTA Photomask Inc., 1605 Remuda Lane, San Jose, California 95112, USA*
[4]*Institut National de la Recherche Scientifique (INRS)—Energie, Matériaux et Télécommunications,*
Varennes, Québec, Canada, J3X 1S2
Corresponding author: slavik@ufe.cz

Received December 8, 2008; revised February 21, 2009; accepted February 24, 2009;
posted March 3, 2009 (Doc. ID 104968); published March 25, 2009

The filtering scheme proposed here is based on transmission through a dual long-period-fiber-grating (LPFG) configuration and enables implementation of arbitrary spectral transfer functions using available inverse-scattering design algorithms, such as those widely used for fiber Bragg gratings (FBGs) operating in reflection. Besides the important technical advantage of operation in transmission, the proposed device can reach large spectral bandwidths that would be extremely challenging to reach by, e.g., FBG devices. The proposed concept is demonstrated by designing and fabricating a LPFG-based filter for synthesis of transform-limited 1.5-ps-long square-like pulses. © 2009 Optical Society of America

OCIS codes: 050.2770, 060.2340, 200.4740, 320.5540.

Photonic linear filters are based on a variety of technologies, including thin-film filters, coupled interferometers [1], and fiber Bragg gratings (FBGs) [2], and they are usually designed using well-established and powerful methods. Among these technologies, photonic filters based on FBGs have attracted considerable attention, particularly owing to their all-fiber nature, which translates into important practical advantages, such as low loss, robustness, ability to handle relatively high powers, and full compatibility with fiber-optics systems. Moreover, virtually any filtering characteristics (i.e., amplitude and phase spectral transfer function) can be obtained when using FBGs in reflection [2]; various design/synthesis algorithms, e.g., inverse-scattering techniques, have been developed for this purpose. Regrettably, this is not true when operating FBGs in transmission, which is a preferred/simpler configuration that does not need any additional device to retrieve the reflected signal (e.g., optical circulators). An alternative to FBGs are long-period fiber gratings (LPFGs) that typically allow coupling of light from the fiber core mode into a copropagating cladding mode and thus operate inherently in transmission. Moreover, LPFGs typically exhibit broader resonance bandwidths than FBGs, which make the LPFG solution better suited for a range of applications. For example, in ultrashort linear pulse shaping and processing, much shorter waveforms can be processed with LPFGs [3] as compared to FBGs [4]. However, LPFGs working in transmission exhibit similar design limitations to those of transmission FBGs. To obtain a filtering process in LPFGs with a similar flexibility to that offered by FBGs operating in reflection (i.e., for arbitrary spectral filtering), the input and output signals would need to be carried by different modes (e.g., input in the core mode and output in the cladding mode, or vice versa) [3,5]. In fact, FBG-like inverse scattering methods having this restriction have been also developed for codirectional grating assisted mode couplers (e.g., LPFGs) [5]. However, it is difficult to couple light in/out of a fiber cladding mode.

We propose here an approach that overcomes this difficulty by employing two different concatenated LPFGs separated by a core light-blocking device [6]. In the proposed LPFG-based arbitrary filtering configuration, both the input and output signals are in the fiber core mode. To "prove the principle," we construct a device for reshaping a Gaussian-like optical pulse into a 1.5 ps transform-limited (dispersion-free) squarelike pulse. Although transform-limited flat-top pulses of similar duration were previously demonstrated using another LPFG-based scheme [7], these methods did not allow for generation of actual squarelike pulses (i.e., flat-top pulses with steep edges). Squarelike temporal pulses have sinclike spectral characteristics; the larger the number of sidelobes in the sinc spectral function, the steeper the edges of the generated squarelike pulse (relative to the total pulse duration). Squarelike pulses previously synthesized with all-fiber devices were either limited in time duration (>10 ps, using FBGs in reflection [4]) or had sinclike spectral characteristics consisting of the main lobe and only the first sidelobes [7], which allowed a flat-top but with relatively smooth falling/rising temporal edges. The squarelike pulses synthesized here are significantly shorter than those achievable with FBGs; in addition, the generated pulses contain two sidelobes in the spectral sinclike characteristics (limited by the input pulse bandwidth).

The *principle of operation* is as follows. We use a short LPFG that couples the light propagating in the core mode into a specific cladding mode within a relatively large bandwidth (Fig. 1). Subsequently, a core mode blocker (CMB) (an attenuating fiber section) absorbs the remainder of light in the core mode. Finally, the second LPFG (hereafter referred to as the "long LPFG"), which is designed using FBG-like inverse-scattering algorithms [5], is used to perform

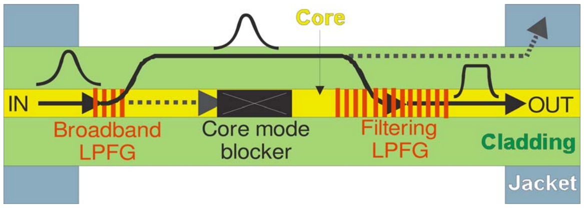

Fig. 1. (Color online) Schematic of the proposed filtering device.

the desired (arbitrary) filtering function with the light being in the cladding mode at its input and in the core mode at its output. CMB reduces parasitic interferences and also ensures that the device behaves like a bandpass filter rather than as a notch filter, which is typical for LPFGs. Similar LPFG-based structures using two identical LPFGs were already reported [8]—the filtering characteristics were, however, influenced by the characteristics of both LPFGs, and thus inverse-scattering algorithms were not directly applicable. Figure 2 shows two examples in which the long LPFG is designed to reshape a pulse emitted by a mode-locked laser (450 fs FWHM with sech^2 temporal profile) into a transform-limited squarelike waveform and into a transform-limited double pulse, respectively. In these two examples, we assume that the long LPFG is uniform; in general, the amplitude and phase apodization profiles of this LPFG will need to be properly tailored to achieve the targeted spectral filtering operation, as determined by the used inverse-scattering synthesis algorithm. For the flat-top pulse generation, the LPFG is 11 cm long, and its coupling strength [3] is $\kappa L = 0.5\pi$. For the double-pulse generation, the LPFG is 15 cm long, and its coupling strength is $\kappa L = 0.85\pi$. The spectral transfer functions provided by the coupling between the selected cladding mode and the core mode in the considered LPFGs are shown in Fig. 2(a). Figure 2(b) shows the spectral energy distribution of the input and the output pulses. The output pulses have the apodized sinclike characteristics that are required for the flat-top and double-pulse generation operations, respectively. Figure 2(c) shows the pulse temporal average optical power calculated from the corresponding field spectrum using Fourier transform. The squarelike pulse is 1.5 ps (FWHM), while the individual pulses in the double-pulse waveform are nearly identical to the input optical pulse, and they are separated by 1.3 ps; achieving these reshaping operations over such short time scales would be very challenging using state-of-the-art FBG fabrication techniques. On the contrary, our configuration can be easily further scaled to shorter waveforms. For example, for generation of a two-times-shorter flat-top pulse, a two-times-shorter LPFG ($L = 5.5$ cm) that can be easily fabricated would be needed.

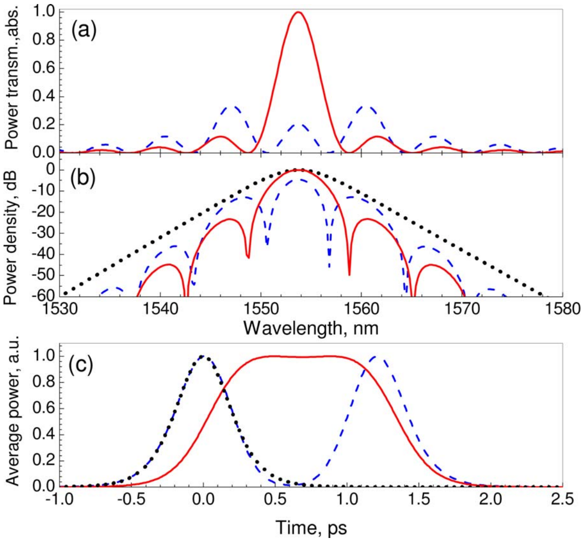

Fig. 2. (Color online) (a) Cladding-to-core power spectral-transfer functions of two long uniform LPFGs designed for square-like-pulse (solid, red) and double-pulse (dashed, blue) synthesis; (b) spectral power densities of the 450 fs FWHM sech^2 input pulse (dotted, black), and the output square-like pulse (solid, red) and the double-pulse (dashed, blue); (c) input (dotted, black) and output (solid, red: square-like; dashed, blue: double-pulse) temporal waveforms.

In the experiment, we chose to demonstrate our device on the above example of transform-limited squarelike waveform generation, in which each input sech^2-like pulse is reshaped into a transform-limited squarelike pulse. The used LPFGs were made using a point-by-point technique with a CO_2 laser. The two LPFGs were inscribed into the PS1250 (Fibercore Ltd., UK) optical fiber and were 7 and 110 mm long. Their respective transmission spectral responses, measured with a broadband light source and an optical spectrum analyzer (OSA), are shown in Fig. 3(a). The long LPFG was slightly overcoupled (coupling strength of 0.6π) in order to obtain the desired first sidelobe transmission level of about 80%. The core mode blocker was made of a 3 cm piece of an "attenuating fiber" with a core mode loss of 14 dB/cm (Coractive Inc., Canada). The amplitude and phase spectral transmission responses of the entire filtering structure were obtained using an optical vector analyzer (LUNA Technologies Ltd., USA) and are shown

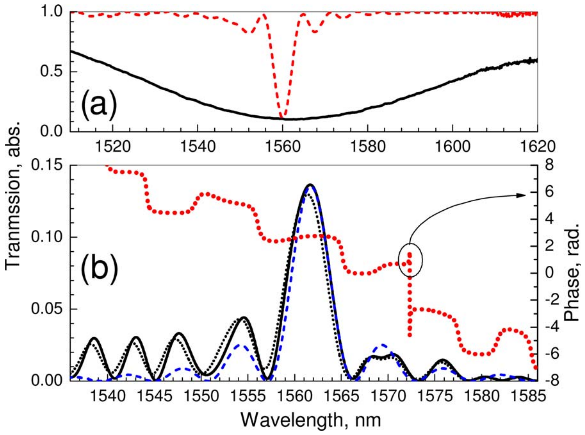

Fig. 3. (Color online) Transmission spectral transfer functions of (a) the two individual LPFGs (short, solid curve; long, dashed curve) and (b) the entire fiber filtering device along both axes of birefringence (solid and dotted curves) together with the calculated curve (dashed curve). The phase measured along one of the principal axes of birefringence is shown with a dotted curve.

in Fig. 3(b). In this figure, the amplitude transmission along the two principal axes of birefringence is presented, showing that the fabricated filter exhibited relatively low polarization sensitivity. For clarity, the phase characteristics are shown only for transmission along one principal axis of polarization. In the measured phase spectral response, we can observe the expected π-phase shifts at each zero transmission point. For comparison, the theoretically expected amplitude spectral response, considering the experimentally obtained insertion loss, is also shown.

The input pulse was generated from a passively mode-locked tunable fiber laser (Pritel, Inc., USA); its energy spectrum is shown in the inset of Fig. 4. The measured autocorrelation width was of 820 fs FWHM, which corresponds to a pulse width of 530 fs, assuming a sech^2 pulse shape. This input pulse was spectrally centered at the LPFG structure peak transmission and subsequently propagated through the LPFG structure. A low optical input-pulse power (attenuated −10 dB from the original average power of 390 μW) was used to avoid optical nonlinearities. Owing to the slight polarization dependence of the in-house-made filter [Fig. 3(b)], the input polarization was controlled with a polarization controller. The amplitude and phase temporal profiles of the reshaped pulse were measured using fiber-based Fourier transform-based spectral interferometry (FTSI), in which the input pulse served as the reference [9]. The experimental results together with the simulated data are shown in Fig. 4: Figure 4(a) shows the spectral energy distribution measured with an OSA, and Fig. 4(b) shows the temporal characteristics obtained with the FTSI. For the simulations, a sech^2 450 fs FWHM pulse with the spectrum shown in the inset of Fig. 4(a) was assumed. This pulse time width is about 15% shorter than that estimated from the autocorrelation measurements, even though the simulated and measured pulse spectral bandwidths are very similar. This discrepancy can be attributed to the fact that the actual pulse spectrum is slightly asymmetric, and thus it does not strictly correspond to the sech^2 pulse shape considered in the analysis of the autocorrelation trace. The ripple in the flat-top section of the synthesized squarelike pulse was measured to be less than 7% (in power). This could be further reduced by better matching the pulse/LPFG filter bandwidths. The pulse phase is almost constant over its temporal duration, which confirms that the synthesized pulse was transform limited. Further, a very good agreement is observed between the expected and measured waveforms in terms of the shape and duration. The measured sinclike spectral characteristics confirmed that the generated pulse had two sidelobes at both sides.

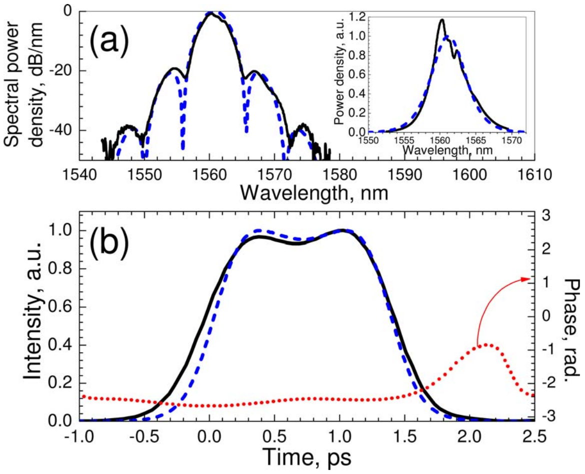

Fig. 4. (Color online) Expected (dashed, blue) and measured (solid, black) characteristics of the generated squarelike pulse in the (a) spectral and (b) temporal domains. The measured phase profile in the temporal domain is shown with a dotted curve. The inset shows the measured (solid, black) and simulated (dashed, blue) input-pulse-energy spectrum.

In conclusion, we have suggested and demonstrated an LPFG-based structure that enables the implementation of arbitrary linear filtering functionalities, following the design obtained from well-developed inverse-scattering algorithms, with a potential to be easily scaled to spectral bandwidths significantly larger than those achievable with FBG filters. In the proof-of-principle demonstration, we constructed an all-fiber filter that reshaped a subpicosecond input pulse generated from a mode-locked laser into a transform-limited 1.5 ps (FWHM) squarelike pulse. The demonstrated device should be of interest for a wide range of applications in which customized all-fiber ultrabroadband optical filters are highly desired, including ultrafast pulse shaping and processing operations.

This research was supported by the Czech Science Foundation (contract 102/07/0999) and by the Natural Sciences and Engineering Research Council of Canada.

References

1. Ch. K. Madsen and J. H. Zhao, *Optical Filter Design and Analysis* (Wiley, 1999).
2. L. Poladian, Opt. Lett. **25**, 787 (2000).
3. M. Kulishov and J. Azaña, J. Opt. Soc. Am. A **22**, 1319 (2005).
4. P. Petropoulos, M. Ibsen, A. D. Ellis, and D. J. Richardson, J. Lightwave Technol. **19**, 746 (2001).
5. R. Feced and N. Zervas, J. Opt. Soc. Am. A **17**, 1573 (2000).
6. R. Slavík, Y. Park, J. Azaña, and M. Kulishov, in *Conference on Lasers and Electro-Optics (CLEO/QELS'08)* (Optical Society of America, 2008), paper CMY1.
7. R. Slavík, Y. Park, and J. Azaña, IEEE Photonics Technol. Lett. **20** 806 (2008).
8. D. S. Starodubov, V. Grubsky, and J. Feinberg, IEEE Photonics Technol. Lett. **10**, 1590 (1998).
9. Y. Park, L. Fangxin, and J. Azaña, IEEE Photonics Technol. Lett. **18**, 1798 (2006).