Chapter

Femtosecond Transient Bragg Gratings

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Abstract

Fiber Bragg gratings (FBGs) have found numerous applications in fiber lasers, sensors, telecommunication, and many other fields. Traditionally, they are fabricated using UV laser sources and a phase mask or other interferometric techniques. In the past two decades, FBGs have been fabricated with femtosecond lasers in either the point-by-point method or by using a phase mask, in a similar configuration as with UV laser sources. In the following, we briefly review the advantages of femtosecond fabrication of fiber Bragg gratings. We then focus on transient FBGs; these are FBGs that exist for a short duration only, for the purpose of all-optical, in-fiber switching and modulation and the possible mechanism to implement them with a high-power femtosecond laser. The theory behind transient grating switching is outlined, and we discuss related experimental results achieved by our group on both permanent grating inscription and the generation of transient (dynamic) fiber Braggs gratings.

Keywords: femtosecond fiber Bragg gratings, transient fiber Bragg gratings, dynamic fiber Bragg grating, all-optical switching and modulation

1. Introduction

Femtosecond laser micromachining and inscription have attracted significant attention in the past decade, not only for material processing applications, such as cutting or drilling [1, 2], but also for the fabrication of 3D photonic devices in transparent materials. When focusing a high-power femtosecond pulse inside a transparent dielectric material, the intensity at the focal region is high enough to initiate multiphoton ionization, which eventually leads to structural changes and permanent refractive index changes [3–7]. This technique has some advantages over current photonic device fabrication methods: (i) the nonlinear nature of the laser-matter interaction confines any induced index change to the focal volume, enabling 3D fabrication of photonic devices in a relatively short time compared to planar semiconductor-based fabrication methods; (ii) the nonlinear absorption process does not require any photosensitivity of the material, facilitating fabrication in glasses, crystals, polymers, and practically any optical material. Although preprocessing of the materials to be inscribed is not necessary, it can be helpful. Hydrogen loading, for example, can enhance the sensitivity to inscription of fiber Bragg gratings [8, 9].

Different categories of index change have been defined in the literature, mostly with respect to grating fabrication. Type I index changes happen for pulse energies

close to the nonlinear ionization threshold (10^{13} W/cm^2) and cause an accumulative change in the refractive index of the order of 10^{-3} (in silica glass). The change in the refractive index is isotropic and is mostly attributed to localized material melting and rapid resolidification [10, 11], although other explanations (such as color center formations) are also considered [12]. This type of index change is most useful for the fabrication of waveguides [13], couplers [14], and FBGs [15].

Type II interaction happens at intensities beyond the damage threshold, which can lead to the formation of voids [16]. Voids are submicron features, micro-explosions in matter, or air bubbles, with larger refractive index contrast compared to their surroundings. They are achieved by extremely tight focusing with power densities of the order of 10^{15} W/cm^2. Voids attract interest mainly due to their potential as permanent highly dense 3D optical data storage materials. In such schemes, each void represents a bit, which can be read with transmitted or scattered light. It was found that voids can also be seized, moved, and merged by femtosecond laser radiation [17]. Type II FBGs, also termed "damage" gratings, have been shown to withstand higher temperatures and can be used as harsh environment sensors [18].

On applying intensities between the above regimes, an anisotropic, polarization-dependent, index change is induced, and the glass material becomes birefringent [19, 20]. The magnitude of the reported index change is the same as for type I changes, but it is not isotropic. The intensity boundaries for this interaction are not well defined, as they depend on the laser source, the focusing lens, and the material itself. The anisotropy of the refractive index change is believed to originate from the nanogratings observed inside the focal volume. The planes of these gratings are perpendicular to the light polarization and behave as negative uniaxial crystals [21–24].

In the following we will focus on fabrication of FBGs using femtosecond laser. Section 2 briefly describes methods of fabrications using femtosecond laser and references to a more detailed work on the subject. Section 3 introduces the main concept of this chapter—transient fiber Bragg gratings for optical switching. The theory of transient grating is outlined, and an overview of various works on the subject is described. Section 4 provides experimental results achieved by our group on generation and characterization of transient FBGs. Finally, we summarize and discuss possible future research direction of transient Bragg grating switching.

2. Femtosecond inscription of fiber Bragg gratings

FBG fabricated with femtosecond laser was first demonstrated by the point-by-point (PbP) method [25, 26]. In this method, the beam is tightly focused into the fiber core to a spot size radius smaller than half of the desired grating period. To achieve this, a microscope objective with a high numerical aperture must be used, as well as pulse energies just above the inscription threshold. The induced index change happens on the pulse peak intensity only, which can be smaller than the diffraction limit of the focusing objective lens. To fabricate the grating, the fiber is aligned and translated in the focal plane at constant velocity. The scan velocity matches the grating period to the laser pulse rate, so that each pulse inscribes a single grating "plane."

The PbP method requires tight control on all-optical and mechanical parameters of the system. The optical system must be carefully aligned to avoid aberrations and achieve the smallest spot size. The pulse width and energy should be controlled as well, since they affect the actual spot size. For this reason, most PbP systems use 800 nm femtosecond laser, rather than its harmonics, to avoid dispersions [27].

From a mechanical perspective, the fiber core must be maintained in the focal plane through the entire fabrication process. This requires high-end air-bearing translation stages. An extension of the PbP method to reduce the mechanical complexity is the line-by-line method, in which the beam is scanned across the fiber axis and forms a rectangular "snake" pattern [28], or plane-by-plane method in which the beam is focused to an elliptic sheet, creating 2D index change [29].

The PbP method offers the highest flexibility in grating fabrication. Uniform gratings, phase-shifted gratings [30], apodization [31], and more [32] have been demonstrated. The tight focusing condition also enables inscription through the fiber jacket without damage [33]. The same inscription system can be used for the fabrication of waveguides and long-period gratings as well [34–36]. Gratings fabricated by this method have been shown to have superior thermal properties [37] than UV gratings and better performance as fiber laser mirrors [38–40].

In 2003, Mihailov et al. demonstrated the fabrication of FBGs with a femtosecond laser and a phase mask [41, 42]. The optical configuration is similar to its UV counterpart. The beam is focused on the fiber core using a cylindrical lens and through a phase mask. The mask period defines the Bragg grating period. In the phase mask configuration, the grating is inscribed as a whole rather than plane by plane. It is robust, repeatable, and typically stationary. As the period is defined by the phase mask, relatively long-focus lenses can be used, which greatly eases alignment and makes this configuration suitable for large core fibers as well. With this technique, grating inscription has been demonstrated in various types of fibers [43–46]. The main drawback of this configuration is the lack of flexibility, as the period is predetermined by the phase mask. Nevertheless, it is possible to tune the Bragg wavelength by introducing defocusing and other aberrations into the inscribing beam. Shifts of more than 300 nm, as well as chirp gratings, have been demonstrated with this method [47, 48]. Inscription through the coating is also feasible in this method with "of the shelf" high-NA cylinder lenses [49–51].

Both methods have been used for fabrication of fiber Bragg grating with superior properties than grating fabrication with UV sources. Femtosecond laser can be used to fabricate gratings in any type of fibers and can withstand higher temperature than UV gratings. The most notable feature is the ability to inscribe grating through the fiber coating, thus maintaining its mechanical strength, and avoid handling issues such as stripping, cleaning, and recoating [52–54].

3. Transient fiber Bragg grating optical switching

All-optical switching has been investigated for a long time by the optical community, in particular for optical communication applications. If successful, it will dramatically increase the throughput in optical links and will enable data switching at speeds and rates far beyond the capabilities of current electronic devices.

Recently, there has been a growing interest in FBGs for optical switching applications. Several works reported implementations of an optical switch by tuning a pre-inscribed grating by means of heat, stress, and other relatively slow processes [55–58]. These methods are based on permanent FBGs, in which any change in the refractive index (heat, cross-phase modulation) or period (induced stress) will shift the grating resonance from the signal wavelength. Such switching mechanisms have several drawbacks due to the inherent physical properties of their operation, which limits their applicability and performance. In the wider context, there have been several reports on the switching of various photonic crystal structures, both for fundamental and for applicative purposes (see, e.g., [59, 60] for some recent reviews).

Transient Bragg gratings (TBGs) can overcome these limitations. These are Bragg gratings of finite duration. In the case of femtosecond gratings in materials, they are expected to be formed at intensities below the threshold for permanent index modification and to exist for the inscribing pulse duration only. Transient gratings in fibers or waveguides are expected to act as a fast switch or modulator by implementing a Bragg mirror with (ultra-) fast decay time.

Several mechanisms are available to implement transient Bragg gratings: the optical Kerr effect, free-carrier recombination in semiconductor materials, and diffusion of thermal gratings. The different mechanisms differ from one to another by the rise and decay time of the switch and by the extinction ratio, i.e., the contrast between on and off states. Such transient gratings can be turned on/off by modulating the illumination beam.

The Kerr effect describes the refractive index change in the presence of high intensities, such as those that are available from high-power femtosecond lasers [61]. The refractive index changes by an amount of $n_2 I$, where n_2 is the material nonlinear index and I is the intensity. The response of the material is instantaneous. For silica fibers, $n_2 \sim 3 \cdot 10^{-16}$ cm^2/W; thus, for an intensity of $I = 10^{11}$ W/cm^2, the refractive index change is of the order of 10^{-5}. Stronger index change is feasible for materials with higher Kerr nonlinearity, such as Chalcogenide or Bismuth fibers [43, 62]. The Kerr grating has a periodic pattern, with the index modulation as described above. A Kerr grating switch is expected to be weak yet with a femtosecond time scale response. Several publications reported on transient Kerr gratings in gas for the purpose of spectroscopy and in bulk semiconductors for studying free-carrier recombination rates [63]. An optical grating based on the nonlinear Kerr effect has been used in the past for parametric wavelength conversion [64] and for chemical spectroscopy [65]. An optical switch based on an optical Kerr grating has only been investigated numerically until now [66–68].

Free-carriers in semiconductor materials are formed upon pulse irradiation followed by excessive charge concentrations. In this case, the refractive index changes due to different charge densities are much higher than due to the Kerr effect. The transient index change of the semiconductor is described by the Drude model of excited free-carriers [69–71] reaching values as high as $\delta n/n \sim 10^{-1}$ [59, 60]. Unlike the Kerr effect, which is instantaneous, the FC excitation is "turned on" fast but typically persists for a time scale of several tens of picosecond to several ns depending on the recombination rate of the generated electron-hole pairs and the diffusion length [63, 72–74]. An optical switch-based free-carrier transient Bragg grating is expected to have better contrast and stronger reflection but on a much shorter switching time. As the reflection is very sensitive to the grating period (typically 1 μm), extremely small diffusion is sufficient to wash out the grating and its reflection. Sivan et al. showed theoretically that when exciting a transient grating based on FC, the turn-off times are very fast (<ps) due to diffusion of the excited FCs that erases the grating structure [75]. This is a key point that will allow for switching times several orders of magnitude faster than in bulk FC switching configurations, thus potentially revolutionizing switching technology. Such an optical switch is expected to have a better extinction ratio than a Kerr grating and slower (picosecond) time scale switching.

The same principle can be applied for transient thermal gratings, in which the index changes as a response to localized heat or increased temperature and the diffusion length is determined by the material properties. Transient thermal gratings are used as a method for measuring the diffusion coefficient of materials and were implemented in opaque materials with linear absorption at the laser wavelength [76–78]. Optical materials are mostly transparent to NIR femtosecond lasers

(800 nm); therefore, a transient thermal grating may only be realized through *nonlinear* absorption.

Another mechanism is to form dynamic population gratings in active fibers. This was implemented via counter propagating waves and resulted in millisecond time responses [79].

TBGs of a few centimeter lengths were implemented using 193 nm, nanosecond, excimer laser pulses, and a phase mask in phosphosilicate fibers without hydrogen loading. In passive fibers, extremely slow reflection of tens of seconds' duration was demonstrated [80], while in active fibers, the grating was based on population inversion, and the time response was estimated to be milliseconds long [81]. In both cases the expected rise time of such switching mechanism cannot be shorter than the ns pulse length.

Transient grating-based switching was suggested numerically by coupling light from the fundamental mode to high-order modes [82]. Nanosecond switching was implemented using the Kerr effect with a highly nonlinear polymer layer deposited close to the core of a polished fiber [83]. It was suggested, theoretically, that a TBG would result in an ultrafast switching response [84]. Thermal phenomena are typically associated with relatively long (microsecond) time scales. Recently, it was suggested, theoretically, that picosecond scale switching is achievable with thermal gratings, using metal nanoparticles in waveguides [85]. Nanosecond switching of a permanent FBG was demonstrated by introducing electrodes into a special two-hole fiber [86]; however, this device suffers from nanosecond rise time and a millisecond time scale to return to its original state.

TBGs essentially enable pulse extraction from CW source. This can lead to several photonic applications such as all-optical switching and modulator at any wavelength, all-fiber Q-switching mechanism, and sub-ns pulse sources.

In the following, we will shortly describe the theory of transient Bragg grating. A detailed derivation of the suitable coupled mode equations, and their numerical solution can be found in literature. Here, we begin our discussion from the coupled mode equations and limit the discussion to specific case where analytical solution is possible to gain physical insight. Next, we will describe our group experimental work on transient Bragg gratings in silica fibers. We will show the dynamic of permanent grating switching and describe an immunization technique that enable, for the first time to our knowledge, thermal grating-based nonlinear absorption.

The theory of transient Bragg gratings is fully developed and described in the literature [87, 88] starting from the wave equation. Here, we provide a short description of the theory starting from its derived coupled mode equation for transient grating. The analysis begins from the well-known coupled mode equations for forward and backward propagating waves in grating media, adapted to the case of transient grating:

$$\frac{d}{dt}A_f + v_g\frac{d}{dz}A_f + 2\,iv_g\kappa q(z)m(t)A_f = iCv_g\kappa q(z)m(t)e^{(-2i\delta\kappa z)}A_b \tag{1}$$

$$\frac{d}{dt}A_b - v_g\frac{d}{dz}A_b + 2\,iv_g\kappa q(z)m(t)A_b = -iCv_g\kappa q(z)m(t)\exp^{(2i\delta\kappa z)}A_f \tag{2}$$

Here, A_f and A_b represent the envelopes of the forward and backward pulses, respectively, v_g is the group velocity, $q(z)$ is the spatial shape of the inscribed Bragg grating, and $m(t)$ is its temporal profile. C is the grating contrast, and $\delta k = \delta\omega/v_g$ is the detuning of the incident pulse from the center of the spectral gap. The forward-backward mode coupling coefficient, $\kappa = k_0 n_0 \Delta n/4n_{neff}$, is a product of the free space wavevector k_0, the waveguide material refractive index n_0, and its maximal

modulation amplitude Δn, divided by the effective mode index n_{neff}. These equations are similar to those obtained in [87]; however, they account for non-zero mean index modulations, absorption, imperfect grating contrast, and nonuniform pumping (via $q(z)$).

An exact solution of Eqs. (1) and (2) is possible only numerically. However, if one assumes uniform pump spot ($q = 1$) and ignores the spatial derivatives (justified for short modulations during which the pulse is nearly stationary), Eqs. (1) and (2) can be solved analytically—this yields the well-known Rabi solution (see, e.g., [87, 89]). This was shown to give a reasonable accuracy in measurements with spin waves [87], at least in this limit, and to lead to envelope reversal [90–92].

Alternatively, Eqs. (1) and (2) can also be solved analytically in the low conversion efficiency limit, without neglecting the spatial derivatives. In this case, the efficiency of the backward pulse generation is given approximately by a convolution of the incoming pulse with $\mathrm{m_{eff}}(t)$, where $\mathrm{M_{eff}}(t)$ is an *effective* modulation, and the forward wave is (nearly) monochromatic (e.g., for a CW or nanosecond source —$A_f(t) \to 1$):

$$A_b(z,t) = iCv_g\kappa q(z)m(t)\mathrm{e}^{\{2i\delta kz\}}M_{eff}(t) \tag{3}$$

$\mathrm{M_{eff}}(t) = q(z) * m(t)$ is the convolution of the (transverse) spatial and temporal profiles of the pump pulse. These equations can be solved analytically assuming symmetric Gaussian shape for the pump pulse: $q(z) = \mathrm{e}^{\left(-\mathrm{z}/\mathrm{L_g}\right)^2}$ and $m(t) = \mathrm{e}^{(-\mathrm{t}/\mathrm{T_{mod}})^2}$.

The complex analytical solution for the backward reflected pulse depends on two time scales: (i) the modulation time T_{mod}, which, for a Kerr grating, is the pump pulse duration, and (ii) the grating pass time $T_{pass} = L/v_g$, where L is the grating length and has the form:

$$|A_b(t,z)| \sim \sqrt{\pi}C\frac{n_0}{4n_{eff}^2}\Delta n\omega_o\sqrt{\frac{T_{pass}^2T_{mod}^2}{T_{pass}^2+T_{mod}^2}}e^{\left\{-\frac{(z+v_gt)^2}{v_g^2\left(T_{pass}^2+T_{mod}^2\right)}\right\}} \tag{4}$$

Significant physical insight is achieved under the assumption that $T_{mod} \ll T_{pass}$. The solution for the reflected wave is then

$$|A_b(t,z)| \sim \sqrt{\pi}C\frac{n_0}{4n_{eff}^2}\Delta n\omega_0T_{mod}e^{\left\{-\frac{(z+v_gt)^2}{v_g^2T_{pass}^2}\right\}} \tag{5}$$

This reveals unique spatial-temporal dependency. The reflected wave has the temporal duration of the longer time scale, and the power is scaled as the shorter time scale. This occurs because the reflections occur from within the grating rather than outside of it. Note that the grating length only influences the temporal duration and not the power efficiency. The reflected efficiency can be approximated to be $\sim \left(\frac{\pi^{\frac{3}{2}}}{2\lambda_0 n_0}\Delta n c_0 T_p\right)^2$.

For a 10^{-4} index change and a 50-fs pump duration with a 1500-nm signal wavelength, we get an efficiency of $\sim 4 \cdot 10^{-6}$. Since $v_gT_p \sim 10\ \mu m$, then the minimal length of the grating for this limit to hold is about 0.1 mm. The backward pulse is then at least 500 fs long.

In the opposite case of a very short grating, $\mathrm{T_{mod}} \gg \mathrm{T_{pass}}$, as is feasible in semiconductors, the reflected pulse power is

$$|A_b(t,z)| \sim \sqrt{\pi} C \frac{n_0}{4n_{eff}^2} \Delta n \omega_0 T_{pass} e^{\left\{-\frac{(z+v_g t)^2}{v_g^2 T_{mod}^2}\right\}} \quad (6)$$

Thus, the reflected wave duration and spectrum follow that of the pump pulse.

The above approximations are valid for low reflection efficiency, i.e., undepleted pump. Transient Kerr grating is expected to have a very low efficiency, and an order of magnitude difference between T_{pass} and T_{mod} is expected to correspond to the above solutions.

In silica fibers, there is also the possibility for thermal gratings. In this case the index modulation time varies on the microsecond and nanosecond time scales, which is considerably longer than the passage time for a typical 5-mm grating (~25 ps). The expected reflectivity should behave as in the first case above with the exception of non-Gaussian response.

The results indicate that with the Kerr mechanism high reflection efficiencies are feasible for Chalcogenide fibers and semiconductor waveguides; however, silica fibers are more challenging. Furthermore, as the reflection from transient Bragg gratings is dependent on the pumping configuration, e.g., grating length and pump pulse duration, and it is possible to control the signal modulation. In the theory, generation pulses on time scale such as tens of ps, currently not available from fiber lasers, are possible. Other interesting applications such as in-fiber Q-switching are also feasible.

In the next sections, we will describe experimental results achieved by our group on the subject of transient Bragg gratings in standard silica fibers for switching and modulation applications. We will describe methods to generate them and their results.

4. Experimental results of femtosecond transient FBGs

4.1 Experimental setup

The experimental setup is standard for FBG inscription with the phase mask technique and is shown schematically below (**Figure 1**). A femtosecond laser (800 nm, 35 fs, 1 KHz) is focused on the fiber core, through a phase mask. The mask period is 2.14 μm, suitable for second-order Bragg gratings at 1550 nm. The fiber to be inscribed is connected to a probe signal source and an Optical Spectrum Analyzer (OSA) to monitor the FBG spectrum or to a fast photodiode (Thorlabs DETO8CFC) to monitor the dynamic effects. The signal source can be a broadband ASE source when characterize permanent FBG inscription or an amplified DFB laser when observing transient, dynamic effect. The probe laser mostly operated in CW mode providing 1 W output power and was operated in pulse mode for Kerr grating experiments.

4.2 Transient Kerr grating

We tried to observe a transient Kerr grating with pulse energies below the inscription threshold in standard SMFs. In these experiments, we monitor the reflection from the grating with a photodiode. We found the permanent inscription threshold to be 160 μJ; thus, our pulse energy is limited below this value. For 100 μJ pulse energy, we expect grating index modulation of $8 \cdot 10^{-7}$, which will exist for 35 fs only. The expected reflection from such a grating is extremely weak; the

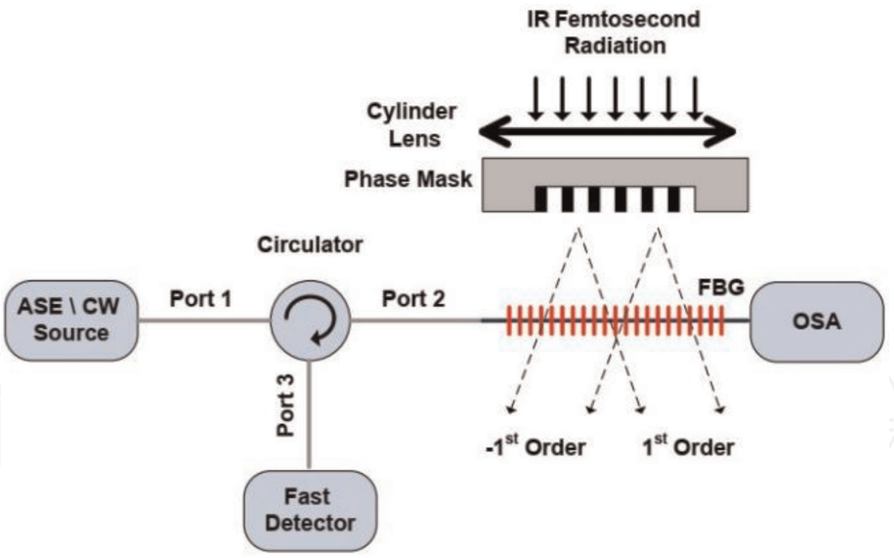

Figure 1.
Schematic of the optical setup.

coupling coefficient, calculated according to the theory outlined in Section 3 is $\kappa \sim 8 \cdot 10^{-7} \left[\frac{1}{\mu m}\right]$, four orders of magnitude lower than typical permanent gratings. Therefore, we drive our probe laser with 50 ns pulses at a 20 KHz pulse rate. In this mode, the laser outputs 1 KW peak power, tuned to the Bragg wavelength. The reflected efficiency expected for such index modulation is $\sim 10^{-5}$.

Unfortunately, we could not detect any Kerr grating reflections with our detector or with a lock-in amplifier. Furthermore, we noticed an increase in the detector DC level, and a photodiode was able to measure a weak (nW) but slowly growing reflected power signal indicating permanent inscription. We repeated the experiment with 50 μJ pulse energy to find again permanent inscription.

The reflected power was extremely weak and could not be detected with a standard ASE source. The permanent inscription may be the result of tunneling ionization rather than multiphoton ionization, which is a much slower process that is expected for relative low intensities by the Keldysh theory [93]. Further investigation is required in order to produce Kerr grating, most likely in a different material with higher nonlinearity. In the following we will present different methods to observe transient gratings based on thermal effects in silica fibers.

4.3 Permanent grating switching

In this configuration, we first fabricate a high-quality (>25 dB) grating and observed light transmitted through it, i.e., we measure the transmission loss of the grating rather than its reflections. To modulate the grating, we block half of the beam and illuminate only half of the permanent grating through the phase mask. Due to the induced heat of each pulse, the refractive index is elevated, causing half the grating to shift to a higher Bragg wavelength, leaving the other half intact. This opens a transmission gap in the grating, allowing a signal, at wavelength matching the grating Bragg wavelength to be detected by the photodiode. Essentially, we temporarily transform a uniform grating into a phase-shifted grating. **Figure 2** shows the time profile of the transmitted signal through the shifted grating.

The switching mechanism is based on induced heat, as if the gratings were placed on a temperature-controlled controller. However, here the switching is done with an ultrafast laser that provides ultrafast rise time. As can be seen in **Figure 2**, the switching time here is about 8 μs, which makes it suitable for Q-switching

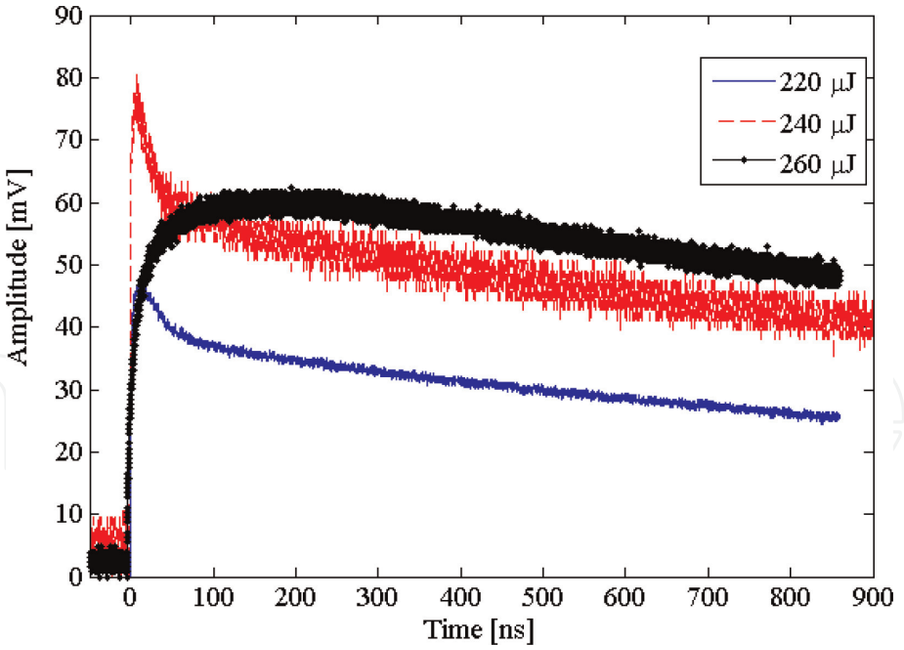

Figure 2.
Pulse measured out of a modulated permanent grating as a function of pulse energy.

applications. We can reduce the switching time to less than 2 μs at the cost of extinction ratio by setting the signal wavelength slightly away from the grating resonance.

While this is a very slow modulation time, it shows the natural response of the induced grating by femtosecond laser pulse at different pulse energies above the inscription threshold. Note that two different regimes are noticeable: for low pulse energies, a fast decay of the signal followed by a long μs tail. When increasing the pulse energy, the fast decay disappears. This indicates the formation of permanent index modification. We will show that the long μs tail can be cut off by performing immunization.

4.4 Immunization to femtosecond inscription

The ability of femtosecond lasers to modify the material refractive index of practically any optical material is a keystone in photonic device fabrication. However, when one wants to observe transient grating effects, it is a drawback, as it limits the applied pulse energy to energies below the multiphoton ionization threshold and permanent index change. It is known that the modified index has a limit, i.e., it can only grow to the order of 10^{-3} (positive change in silica fibers) when it reaches saturation. Reflection from a transient grating, however, depends on both the index modulation and the grating period.

We have found that femtosecond photo pre-treatment can immunize a fiber up to a certain illumination intensity [94]. In fact, the reported multiphoton ionization and inscription threshold ($\sim 10^{13}$ W/cm^2) can be raised so that permanent Bragg gratings first appear at a higher pulse energies.

Fiber immunizing can help avoid permanent index change and observation of transient FBG effects. After immunization, the fiber transient index change effects, such as heat or Kerr, are expected to be observed more clearly as the permanent index change is saturated and its effects are suppressed.

In order to immunize the fiber against femtosecond inscription, we remove the phase mask and inscribe it with a focal line pattern. The pulse energy in this

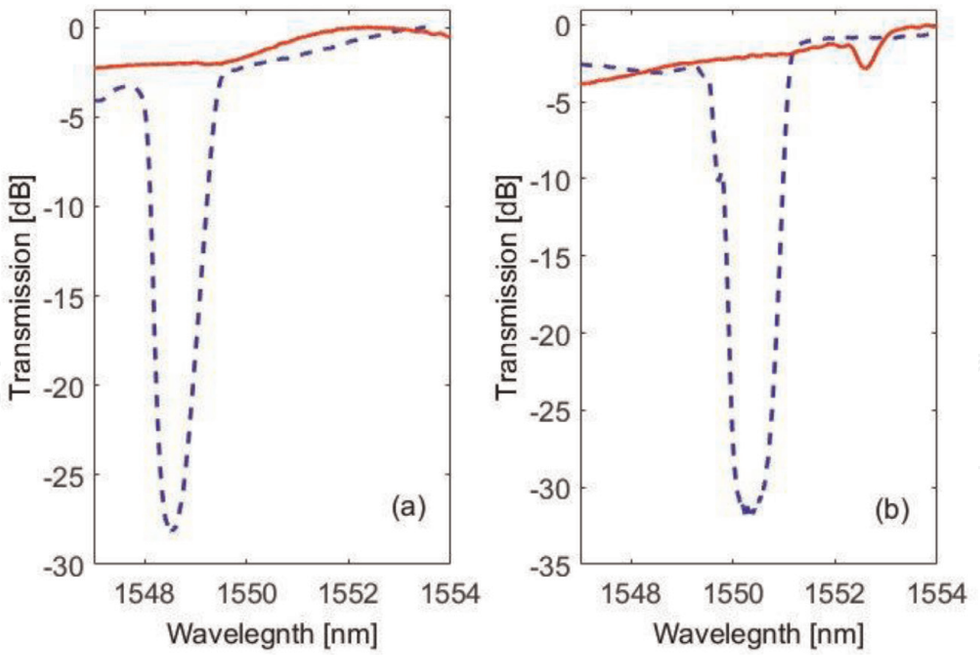

Figure 3.
Transmission spectra of the inscribed permanent FBGs in untreated and treated fibers: untreated fiber, dashed blue lines; treated fibers, solid red lines. (a) 160 μJ pulse energy. (b) 180 μJ pulse energy.

pre-treatment was chosen to be slightly more than twice the average energy for FBG inscription, so that the peak intensity of the pre-treatment would be slightly higher than that of the FBG inscription.

Figure 3 shows permanent gratings inscribed on a fresh fiber compared to a treated fibers. Before any pre-treatment, gratings with −25 and − 30 dB transmission dips were inscribed, at pulse energies of 160 μJ (**Figure 3a**) and 180 μJ (**Figure 3b**), respectively. As is evident, when pre-treatment of the fibers is done at slightly more than double of the pulse energy, the results is a complete immunity for inscription at 160 μJ and in only −2 dB transmission loss at 180 μJ. For the latter, a 2.5-nm wavelength shift is observed, corresponding to an increase of $\sim 2 \cdot 10^{-3}$ of the average refractive index due to the pre-treatment. Thus, our treatment greatly reduces the ability to inscribe gratings. Pre-treatment of the fiber causes complete immunity or limited grating buildup at a considerably lower rate.

4.5 Fast switching with transient thermal grating

Fiber immunization extremely limits the grating buildup. We characterized the transient grating reflections of an immunized fiber [95]. After completing the photo-treatment process on a standard SMF at a pulse energy of 1 mJ, the pump laser pulse rate was lowered to 2 Hz in order to reduce the average thermal effects, and reflected pulses were measured with our detector. **Figure 4a** shows the averaged time trace (100 pulses) of the reflected pulse for different femtosecond illumination pulse energies (all below half of the immunization pulse energy).

The reflected pulses (**Figure 4a**) have a very fast rise time followed by nanosecond decay. This is three orders of magnitude improvement compared to transient grating based on UV laser reported in Ref. [80, 81]. The observed transient increase in the reflectivity can mainly be attributed to local heating of the silica, due to *nonlinear* absorption, corresponding to a local increase in the refractive index and is followed by thermal diffusion that washes out the grating. The decay time is typical for thermal diffusion at these sizes and distances.

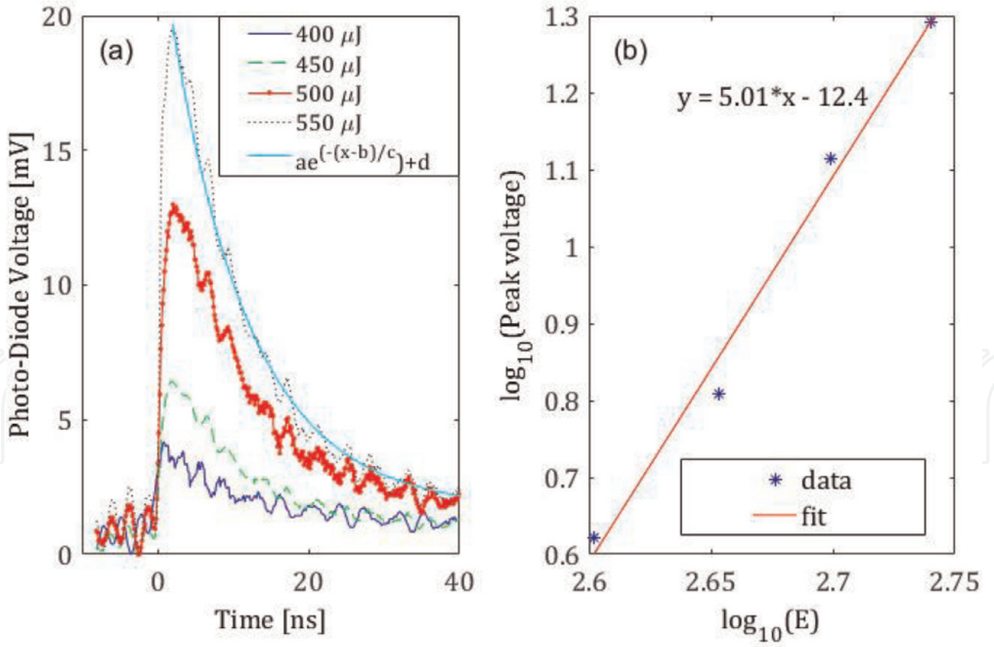

Figure 4.
(a) Measured average time trace of the reflected pulses for different femtosecond illumination pulse energies. The inscribing pulse rate was 2 Hz. An exponential fit with parameters, a = 17.87, b = 2.06, c = 10.5, and d = 1.7, is shown for the highest reflectivity, indicating a thermal diffusion time of ~10 ns. (b) The peak amplitude of the measured reflected signal as a function of pulse energy. The linear fit indicates a nonlinear relation between the pulse energy (intensity) and reflectivity.

The measured rise time is 2 ns, but we believe the actual rise time is significantly shorter, since our measurement was limited by our detection system (about the same rise time was also measured for our 35 fs laser source). For a 550 μJ illumination pulse, the reflected pulse duration is approximately 14.3 ns (measured between 1 and e points). An exponential fit is shown (light blue) in **Figure 4a**, with a time constant of ~10 ns. For a 550-μJ illumination pulse, the measured reflected peak power is 0.38 mW, corresponding to a peak power reflectivity of 0.0435%.

Assuming an effective grating length of 5 mm, and applying the theory for spatial-temporal gratings, we estimate an index change of $\Delta n = 2.3 \cdot 10^{-6}$. This is three orders of magnitude less than reported in the literature for permanent femtosecond inscribed gratings. However, it should be noted that tens of thousands of pulses are used to achieve the reported Δn for permanent inscription. The thermal grating, and the refractive index increase, decay time depends on the diffusion coefficient of the fiber and the grating period. In this case, the decay time expected to be 34 ns [96]. The reflected power from a temporal grating is proportional to $(\Delta n)^2$; thus, we expect from theory (Eq. (6)) a reflected signal decay time of 17 ns. This is in good agreement with the experimental results, where differences may arise due to the presence of germanium in the fiber core.

Figure 4(b) shows the peak reflectivity as a function of applied pulse energy. A small increase in the inscribing pulse energy results in a higher induced transient refractive index change, leading to a significantly stronger reflected pulse. As suggested by the linear fit, the peak reflectivity has, indeed, a nonlinear growth that corresponds to I^5, which is a good indication that the grating is, indeed, based on multiphoton absorption.

With respect to **Figure 2**, and time scale reported with femtosecond induced index change [4], the immunization technique allows us to remove transient effects associated with material resolidification and access the previous phase of femtosecond laser-matter interaction.

We also note here that thermal grating diffusion time is highly dependent on grating period. The diffusion time is opposite to the square of the grating period; thus, working with first-order grating can reduce the time scale by a factor of four. The applicability to transient thermal grating for higher pulse rate and life time of such device is elaborated elsewhere [95].

5. Conclusions

Transient fiber Bragg gratings has a great potential for all-optical, all-fiber, fast optical switching. Many challenges have yet remained to be investigated in this field, mostly improving the efficiency of the grating for practical applications, methods to generate them, and life time of such devices.

Achieving Kerr gratings for ultrafast switching is challenging in silica fibers since the effect is much weaker than inscription of permanent gratings. However, it may be feasible in highly nonlinear fibers or waveguide materials. Semiconductor waveguides and materials are promising for both Kerr-based transient gratings and free-carrier-based gratings. Furthermore, it should be possible to implement with low-power, low-cost diodes rather than high-power femtosecond lasers—at the cost of slower rise time.

The immunization technique presented here can be used to implement transient thermal gratings in transparent materials and may serve as a diagnostic tool for dielectric materials with different compositions and doping. Furthermore, the diffusion of transient thermal gratings is highly dependent on the grating period; thus, many time scales and wavelengths are accessible by simply choosing a suitable mask and illuminating wavelength.

Several applications may rise from transient gratings in fibers and remain to be demonstrated: fiber laser Q-switching and modulation, generation of sub-ns pulses—a regime not accessible with Q-switching or mode-locking technique, diagnostic tools, and more.

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