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Fiber Bragg gratings for optical telecommunications

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Abstract

Bragg gratings photoimprinted in optical fibers have become essential for flattening the gain of amplifiers, stabilizing the wavelength of pumps or sources, and for fiber lasers. Advantages are low insertion loss, very low polarization sensitivity and an extremely flexible design. Those advantages make gratings also very attractive candidates for applications of complex filtering or precise chromatic dispersion compensation. This article briefly describes the different types of Bragg gratings as well as several examples of applications in optical telecommunications. ***To cite this article: I. Riant, C. R. Physique 4 (2003).***

Résumé

Les réseaux de Bragg photoinscrits dans les fibres optiques sont devenus indispensables pour l'égalisation du gain des amplificateurs, la stabilisation en longueur d'onde des pompes ou des sources, et pour les lasers à fibre. Leurs atouts majeurs sont de faibles pertes d'insertion, une très faible sensibilité à la polarisation et une conception extrêmement flexible. Ces atouts en font également des candidats très attractifs pour les applications de filtrage complexe ou de compensation de dispersion chromatique fine. Cet article décrit brièvement les différentes familles de réseaux de Bragg ainsi que quelques exemples d'applications dans les télécommunications optiques. ***Pour citer cet article : I. Riant, C. R. Physique 4 (2003).***

Keywords: Bragg gratings; Optical fibers; Optical telecommunications

Mots-clés : Réseaux de Bragg ; Fibres optiques ; Télécommunications optiques

1. Introduction

Fiber components, such as photo-induced fiber gratings, fused couplers and tapers have become essential for the implementation and growth of optical communication systems. Indeed, they have many attractive attributes. First, they are easily spliced to transmission fibers and other fiber components. Consequently, they exhibit low insertion loss compared to similar planar-waveguide or micro-optic components, where connection to external devices is more difficult. Second, they generally present extremely low polarization sensitivity. Yet it is also possible to achieve polarization-sensitive devices if the goal is to control polarization, for instance. Because light remains in the fiber, fiber components are robust and relatively free from mechanical disturbances. They are also easily customized and can be designed/manufactured in very short times compared to other component technologies. Besides inherent advantages in being fiber components, *photo-induced in-fiber Bragg gratings* (IFBG) furthermore exhibit great design flexibility and high spectral efficiency. Today, fiber gratings are mostly used as gain equalizers where their transmission spectrum is made to smooth the gain ripple of an erbium doped fiber amplifier (EDFA) and as laser-diode pump stabilizers at 1480 nm and 980 nm, where the grating is written on the pig-tail fiber.

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2. IFBGs

The IFBGs are realized by transversally exposing the fiber core to an interference pattern of ultraviolet light as shown in Fig. 1 [1]. A permanent variation of the refractive index is then induced which perturbs the mode propagation in the optical fiber [2]. By properly choosing the period of the perturbation and by tailoring the index variation, filtering functions based on mode-coupling, can be realized. The refractive index change under irradiation is called *photorefractive* effect. It occurs when the material is *photosensitive*. In most cases, fiber photosensitivity is due to the presence of Germanium in the core or in the cladding. The mechanisms underlying the photosensitivity process have been the center of numerous investigations over the last 10 years, and several models have been proposed to explain photorefractivity. Among the most important are the 'colored-centers' model [3] based on a modification of the absorption spectrum, and the model of 'photo-induced densification' [4]. Photosensivity can be enhanced by two orders of magnitude when the fiber is preliminarily hydrogen-loaded. Thus, index variations up to 10^{-3}–10^{-2} can be obtained, which is considerable in comparison with the value of the index step of a standard transmission fiber, i.e., around 5×10^{-3}. The photorefractive effect is permanent, since it remains when the laser light is removed, contrarily to the same effect in photorefractive crystals. After irradiation, however, the induced index variation

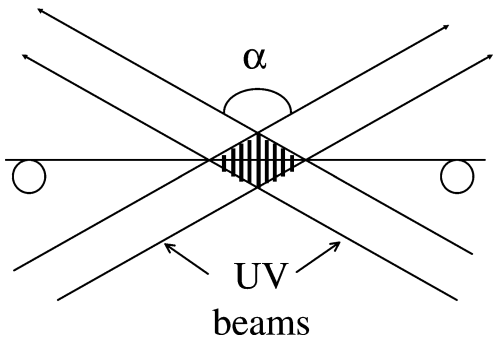


Fig. 1. Principle of the transverse photo-inscription of a fiber Bragg grating.

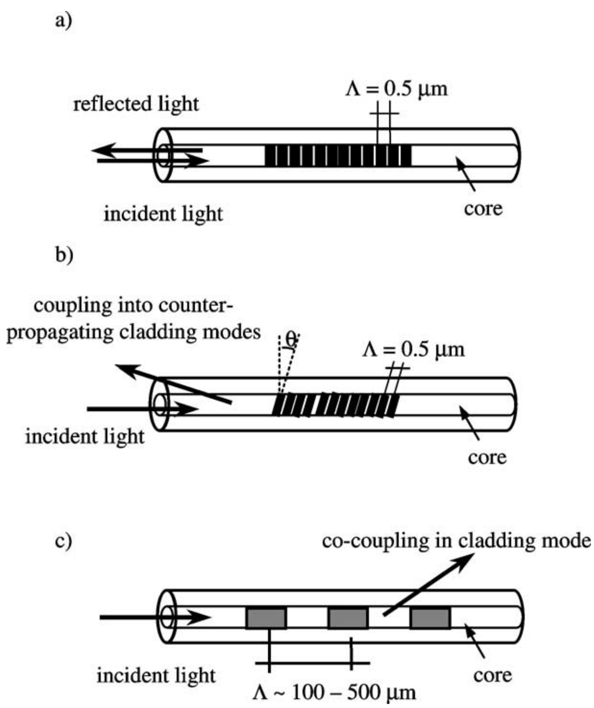


Fig. 2. Schemes respectively of (a) a straight short-period grating; (b) a slanted short-period grating; and (c) a long-period grating. The period of the grating is Λ. For the slanted grating, the lines of the grating form an angle θ with the normal to the fiber axis.

decreases with time, rapidly at first and then stabilizes itself. Several models have been proposed to explain this decay and predict the 'lifetime' of the IFBG. They also show that it is possible to accelerate their ageing by treatment at high temperature, which stabilizes their response for suitable use in system applications [5,6].

The IFBGs can be divided into two types: the short-period (∼0.5 µm) and the long-period gratings (∼100–500 µm). These are schematically represented in Fig. 2. When 'phase matching' is satisfied, the first type generates a coupling between the co-propagating and contra-propagating *guided* modes, while the second type provokes a coupling between the co-propagating guided mode and the co-propagating *cladding* modes.

The grating fringes can be photo-imprinted perpendicular to the fiber axis or at an angle. In the case of short-period gratings, the straight fringes couple the co-propagating and contra-propagating guided modes at a wavelength (λ_B) proportional to the product of the mode effective index n_{eff} times the grating period Λ:

$$\lambda_B = 2n_{eff}\Lambda. \tag{1}$$

An example of experimental spectra in transmission and reflection for a 3.5 mm-long uniform grating written into a standard telecom fiber is given in Fig. 3. It is noteworthy that the two spectra are not complementary. Some oscillations, not present in the reflection spectrum, appear in the transmission spectrum at wavelengths lower than the Bragg wavelength λ_B. Those losses are due to an excitation of the contra-propagating cladding modes by the fundamental guided mode. Several solutions have been proposed to limit this coupling; however, the technique mostly used today consists in using specific fibers with both core and cladding photosensitivity [7]. The filtering bandwidth can be very narrow (<0.1 nm) when the grating is long (several tens of millimeters). It is broader when the grating is shorter. It can be widened up by 'chirping' (varying) the period along the grating.

The introduction of an angle θ between the grating fringes and the normal to the fiber axis makes the coupling efficiency between the two counter-propagating guided modes decrease and the coupling efficiency of the guided mode into cladding modes or radiation modes in a counter-propagating direction increase. Although strongly attenuated, the coupling between the two counter-propagating guided modes still occurs and leads to a residual back-reflection at the Bragg wavelength λ_B which is defined by the following:

$$\lambda_B = \frac{2n_{eff}\Lambda}{\cos\theta}. \tag{2}$$

The coupling between the propagating fundamental mode and the counter-propagating cladding modes takes place at wavelengths shorter than λ_B. At those wavelengths, there is no reflection. This is illustrated in Fig. 4 which shows a transmission spectrum computed for a 4 mm-long slanted Bragg grating written in a standard telecom fiber with angle $\theta = 5.5°$. The Bragg wavelength appears around 1572 nm and, in the rest of the spectrum, some peaks are clearly be observed. The fiber is supposed to be without any coating and surrounded by air. Those peaks correspond to the coupling between the fundamental mode and discrete cladding modes. Immersing the grating into a liquid, or surrounding it by a coating whose refractive index matches that of the cladding, destroys the well-defined limits between cladding and air, and transforms the discrete cladding modes into a continuum of radiation modes. This smoothes the spectrum. However, the specifications of the grating depend upon the adherence and the properties of this surrounding medium. It has then been proposed to make this grating completely independent of any packaging by widening each unitary filter associated to each discrete cladding mode, so that they overlap and suppress the peaks present in the spectrum [8]. The broadening can be obtained by shortening the length of the grating or chirping its period. The spectrum is then smooth and can be used for filtering.

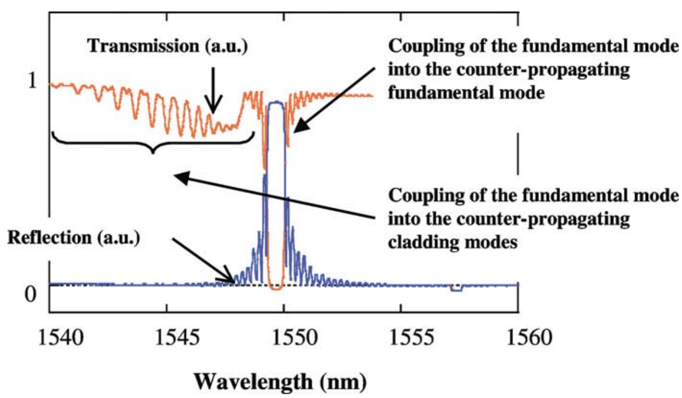


Fig. 3. Experimental transmission and reflection spectra of a uniform straight short-period grating. Length is 3.5 mm.

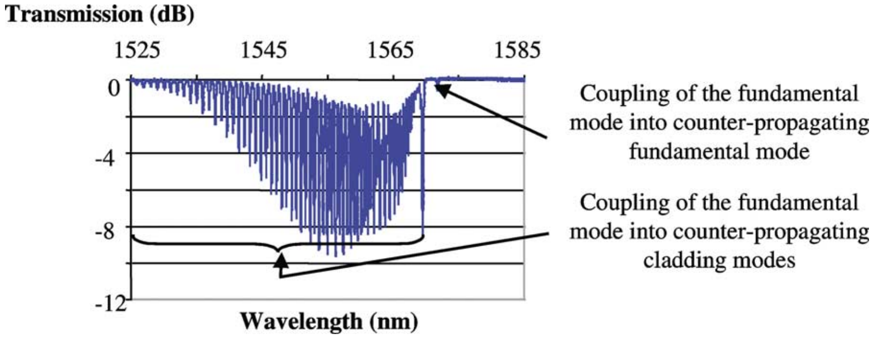


Fig. 4. Experimental transmission spectrum of a 4 mm long grating written in a standard telecom fiber with an angle of 5.5°.

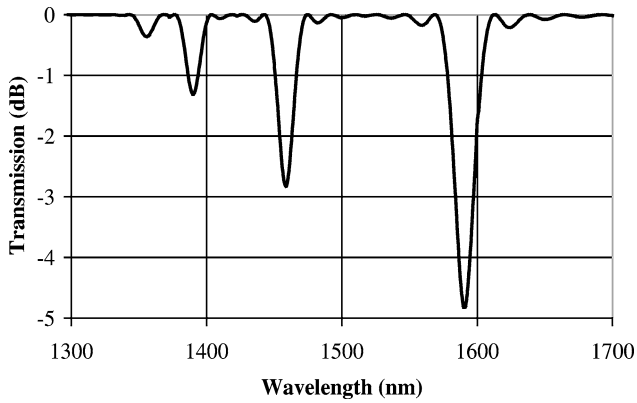


Fig. 5. Transmission spectrum of a long-period grating. Length of the grating is 25.4 mm and the photo-induced variation is 3×10^{-4}.

A long-period grating introduces a coupling between the fundamental guided mode and co-propagating cladding modes. Fig. 5 shows the transmission spectrum of a long period grating photo-imprinted in a standard telecom fiber. The grating length is 25.4 mm and the photo-induced index variation is 3×10^{-4}. Four peaks appear in the wavelength range from 1300 to 1700 nm. Their spectral width is relatively large, i.e., tens of nanometers. In the wavelength range of interest, there is often only one peak. The peak wavelengths are defined as follows:

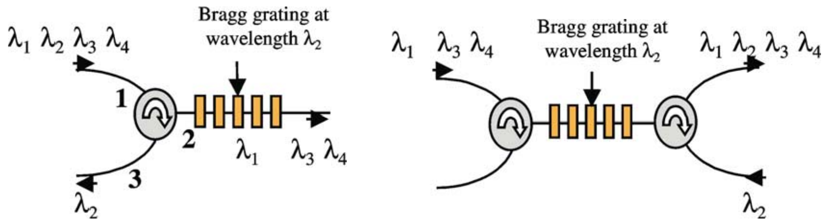
$$\lambda_{\mathrm{m}} = (n_{\mathrm{eff},01} - n_{\mathrm{eff,m}})\Lambda = \Delta n_{\mathrm{eff}}\Lambda, \tag{3}$$

where $n_{\mathrm{eff},01}$ and $n_{\mathrm{eff,m}}$ represent the effective indices of the fundamental guided-mode and the cladding-mode of order m coupled to the guided-mode by the grating, respectively. Coupling occurs for periodicities of several hundreds of microns, which is three orders of magnitude longer than in short-period gratings. The proportionality of the wavelength with Δn_{eff} makes long-period gratings be naturally more sensitive than short period gratings to environmental parameters such as temperature, bending, or the outer medium. This can also be used to make the long-period gratings temperature-independent by designing specific fibers [9,10]. They are also more difficult to time-stabilize [11].

Applications of IFBGs in telecommunication are numerous and diversified. Providing an exhaustive list of those applications would be a task. Therefore, a selection of a few representative examples is only described here.

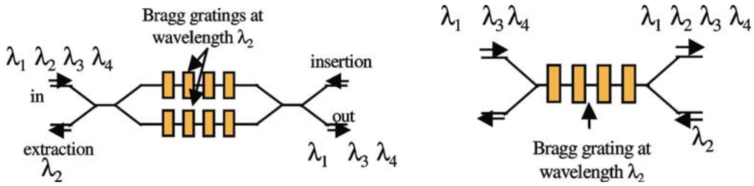
3. Filtering and multiplexing

Acting as wavelength-selective filters, straight short-period gratings were first targeted towards applications of filtering and multiplexing. The reflection coefficient, for weak gratings, is proportional to the Fourier transform of the photo-induced index variation longitudinal profile. The filtering spectrum can then be tailored, by adjusting the period and the photo-induced index variation of the grating, for high rejection of the adjacent channels, rectangular shapes, multi-peaks [12], etc. Today, advanced IFBG writing techniques associated with sophisticated inverse-modeling techniques – permitting the computation of the grating profile from the targeted function – allow the realization of almost any desired spectral shape with control of the phase response



(a) (b)

Fig. 6. (a) Pass-band filter made of a Bragg grating associated with a circulator; (b) Optical add and drop multiplexer made of the association of a Bragg grating with 2 circulators.



(a) (b)

Fig. 7. (a) Optical add and drop multiplexer based on a Mach–Zehnder interferometer: 2 identical Bragg gratings are photowritten at wavelength λ_2 in the 2 arms of the interferometer. The function extraction of λ_2 is represented; (b) Optical add and drop multiplexer based on a 0% coupler: a Bragg grating is photowritten at wavelength λ_2 in the coupling region. The function insertion of λ_2 is represented.

[13]. Fiber gratings are then excellent candidates for future WDM systems requiring complex, but low-cost filters to be adapted to system designs. Demonstrated examples are for instance low channel spacing filters (down to 25 or 12.5 GHz) exhibiting simultaneously rectangular shapes and zero in-band dispersion [14], or pulse-reshaping filters [15].

The straight short-period grating reflects light close to the Bragg wavelength and remains transparent to the other wavelengths. To be used in networks, the grating must be associated to another component with several ‘in’ and ‘out’ ports, in order to extract this signal of interest. Generally, this component is a *circulator*. Its principle is described in Fig. 6. In the same figure, it is also shown that, by placing a second circulator, the function ‘insertion’ can be included in the component. The filter is then transformed into an optical add-and-drop multiplexer (OADM). However, circulators are costly and lossy. It is possible to replace them by all-fiber devices, such as a Mach–Zehnder interferometer where identical gratings are photo-imprinted in the two arms [16], or a 100% (or 0%) coupler where a grating is written in its coupling region [17]. Such solutions are illustrated in Fig. 7. While the first solution is already commercialized, the second one still suffers from low isolation between ports.

4. Compensation of chromatic dispersion: wideband, tunable

The *chromatic dispersion* of the transmission fiber is, with *polarization mode dispersion* (PMD), one of the major limiting factors for increasing bit rate. Pulses are not completely monochromatic, and in dispersive fibers, the different frequencies of the pulse spectrum propagate at different speeds, thus causing pulse broadening. The pulses can overlap, which deteriorates the transmission of the information. The problem worsens when the bit rate increases. Indeed, when the bit rate is higher, the pulses are temporally shorter and thus spectrally broader. Transmission fibers have positive dispersions around 17 ps/nm/km at 1550 nm. In installed systems, lengths of highly-negative dispersion fibers are regularly added for compensation. However, long lengths are required – about 20 km for 100 km of transmission fiber – which represents a large volume. Compensating fibers exhibit more attenuation than transmission ones (0.5 dB against 0.2 dB/km), which brings extra loss to be compensated for by adding amplifiers in the line. Furthermore, those fibers are sensitive to nonlinear effects. The use of a linearly-chirped grating to replace the dispersion-compensating fibers has thus received much interest during these last years. Such a grating is used in reflection in association with a circulator, with its large periods placed first behind the circulator. The principle is shown in Fig. 8. The longer wavelengths are immediately reflected while the shorter ones propagate a little longer, introducing time delay. The solution is attractive since it exhibits low loss (mainly attributable to the circulator), low volume and insensitivity to nonlinear effects.

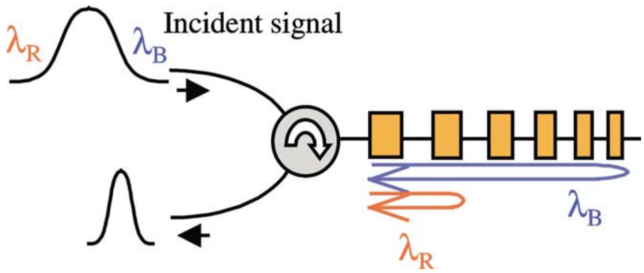


Fig. 8. Principle of chromatic dispersion compensation using a linearly chirped Bragg grating with a circulator.

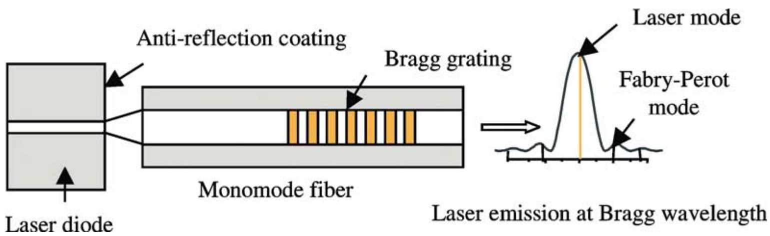


Fig. 9. Laser diode with Bragg grating for wavelength control of the laser emission.

The dispersion introduced by a grating-based compensator can be approximated by the expression (4):

$$DC = \frac{2n_{\mathrm{eff}}L}{c\Delta\lambda} \cong \frac{10L_{(\mathrm{mm})}}{\Delta\lambda_{(\mathrm{nm})}}\ (\mathrm{ps/nm}) \tag{4}$$

where L and $\Delta\lambda$ represent the length and the wavelength variation along the grating (the 'chirp'), as expressed in millimeters and nanometers, respectively. The effective index n_{eff} of the core mode and c the velocity of light have been replaced respectively by 1.45 and 3×10^8 m/s. The formula shows that dispersion compensation of 100 km of transmission fiber is possible for one channel (<0.5 nm) using a grating of length lower than 100 mm. In WDM systems, such gratings must be concatenated for each channel [18]. However, an ideal solution would compensate dispersion over the whole EDFA passband (C-band), representing about 30 nm, using a unique grating. This would require a 5 m-long device. Furthermore, on such wide spectral bands, the compensation of 1st-order chromatic dispersion is not sufficient, it is also necessary to compensate its 2nd-order or slope: this can be done using a quadratically-chirped grating. New techniques of fabrication have then been developed for the realization of long gratings. In these techniques, the apparatus that forms the UV interferences or the fiber is shifted during the photoinscription using interferometrically-controlled set-ups [19–21]. Although considerable progress has been made, those very long gratings, of length greater than a meter, still suffer from low realization reproducibility and high ripple in group-delay response. On the other hand, dispersion-compensating fibers are today of better quality and new techniques are being developed, such as the one based on the propagation of a higher-order mode (HOM) in a *two-moded* fiber. Nevertheless, the flexibility in the design and the mastering of the fabrication of complex gratings are now so high that chirped fiber gratings, of length up to several hundreds of millimeters, still remain an excellent solution to finely compensate residual chromatic dispersion at about all orders [13].

For high bit-rate transmissions (>10 Gb/s), chromatic dispersion must be very precisely compensated, i.e., within several hundreds or tens of picoseconds. However, a variation of temperature is enough to make the dispersion change within these values. It then becomes necessary to continuously compensate chromatic dispersion channel by channel. Gratings of lengths shorter than 100 mm can then be used and dispersion can be tuned by modifying the 'chirp' using the dependence of the wavelength versus temperature [22] or strain [23]. Here again, IFBGs are attractive candidates for such applications.

5. Laser diodes

Although studied for years, photoinscription of IFBGs in the pigtail of laser-diodes to select a wavelength anywhere in the diode gain bandwidth, is getting renewed interest for low-cost WDM sources [24]. The principle is shown in Fig. 9. The diode-chip and the grating can be packaged in a plug-and-play concept, wavelength selection being made by simply choosing the right grating while keeping the same chip. The use of 'comb' filters, such as represented in Fig. 10, is also of high interest for multi-wavelength or tunable sources [12].

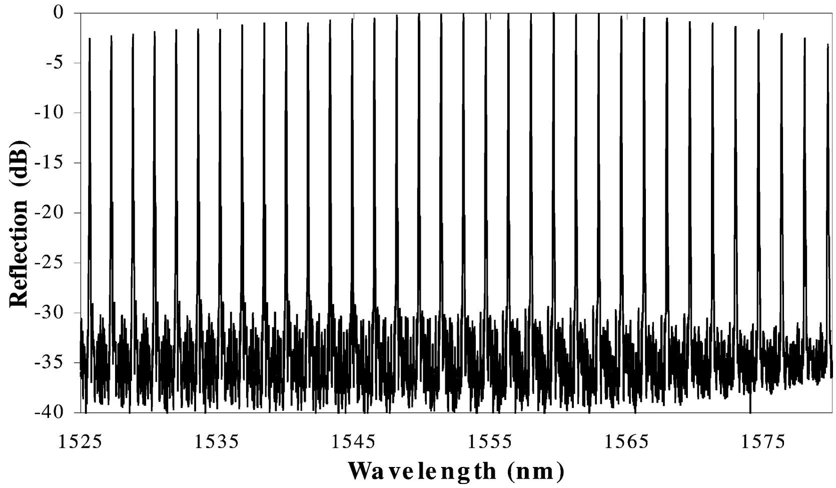


Fig. 10. Spectral response of a "comb" filter with peaks spaced by 200 GHz.

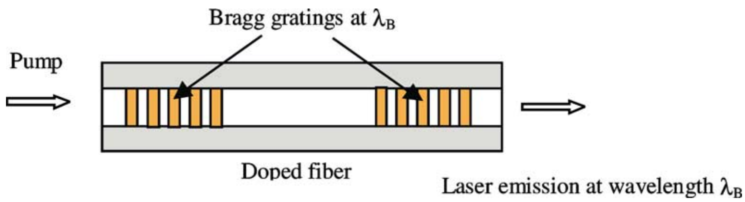


Fig. 11. Fiber laser with photo-imprinted Bragg gratings at wavelength λ_B.

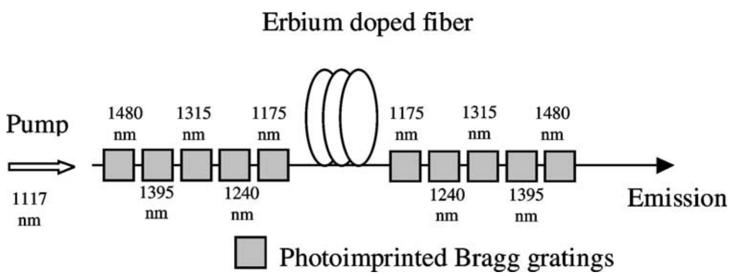


Fig. 12. Raman fiber laser at 1480 nm using Bragg gratings in cascade.

One of the first commercial use of UV-written Bragg gratings was the stabilization of laser pumps in EDFAs, especially pumps at 980 nm. Here, a low-reflectivity grating is placed at a distance (50–100 mm) from the laser diode larger than the coherence length of the laser to provoke an incoherent feedback called 'coherence-collapse'.

6. Fiber lasers

The photo-inscription of fiber Bragg gratings is the optimum solution to close the cavity of *rare-earth-doped fiber lasers*. Directly written in the doped fiber or, alternatively, in a pigtail fiber to be easily spliced to it, those mirrors are integrated with low loss. Lasers emitting at various wavelengths can be realized by properly choosing the dopant and the grating wavelengths. Examples of laser wavelengths are 1.5 µm with erbium as the dopant, 1.3 µm with thulium, etc. Lasers based on the Raman effect, whose principle is described in Fig. 12, have recently gained strong interest. A cavity with a length of tens of meters is closed by pairs of mirrors strongly reflecting at Stokes wavelengths spaced by 13.2 THz and transparent at other wavelengths [25]. Ideal for this application, IFBGs have largely contributed to the development of Raman lasers.

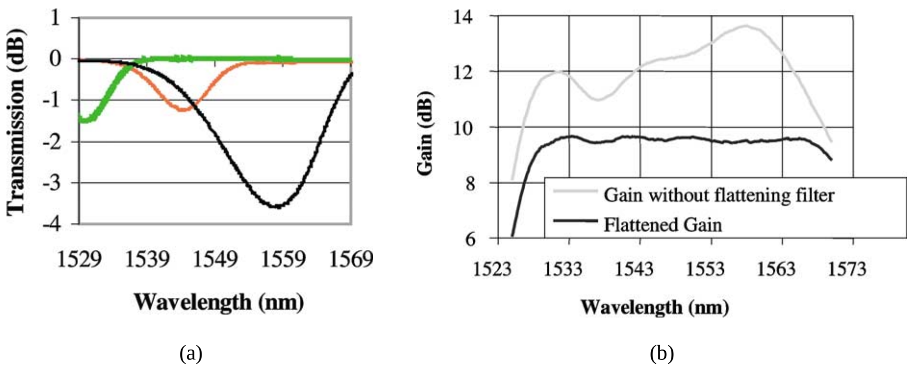


Fig. 13. (a) Experimental transmission spectrum of a cascade of 3 slanted gratings photo-imprinted in different fibers with specifically tailored index and photosensitivity profiles. The two thin lines represent the targeted tolerance around the specifications: (b) Erbium doped fiber amplifier gain with and without equalizing filter.

The possibility of tuning the IFBG wavelength, using temperature or a deformation, allows continuous tunability. The association of several pairs of gratings at different wavelengths, allows one to realize *multi-wavelength lasers*. Those multiple gratings can also be replaced by a 'comb' filter, as mentioned above.

7. Amplifiers

The *gain flattening* of EDFAs, essential in WDM transmission, is today one of the major applications for IFBGs [8]. The insertion of an optical filter whose spectrum matches the inverse of the EDFA gain ripple is today the unique solution. The IFBG can be readily spliced to the erbium-doped fiber and easily customized to any gain-ripple characteristics [26].

Standard short-period gratings are commonly used for gain equalization [27]. The grating period is chirped and the photo-induced index modulation is tailored to shape the spectrum. Their only disadvantage is the necessity of adding an isolator to suppress the back-reflection into the amplifier. As previously mentioned, two other types of grating can overcome this problem of back-reflection: the slanted short-period grating and the long-period grating.

Substantial work was recently carried out to make usable as gain equalizers the envelope of the different couplings into cladding modes, as created by slanted short-period gratings [8,28,29]. Fig. 13(a) shows the experimental transmission spectra of three slanted gratings, that have been chirped for smooth envelopes. They have been realized in different fibers with specially tailored index and photosensitivity profiles. The first two gratings have back-reflection in the overall filtering bandwidth. They have been made in a fiber optimized for ultra-low back-reflection. The third grating has been realized in a fiber optimized for obtaining a straight edge at longer wavelengths. The spectral shape of this grating is slightly asymmetric. The cascade of those three gratings forms a filter that flattens the gain of an EDFA within a variation of 0.22 dB over a 36 nm bandwidth from 1530.5 nm to 1567 nm. The gain curves are represented in Fig. 13(b) with and without equalizing filter. The back-reflection is below –34 dB and the template of the whole shape of the gain flattening filter is respected within a tolerance of $+/-0.05$ dB [8,29].

For long-period gratings, back-reflection is negligible. As for straight short-period gratings, the spectral shape is mostly given by the grating index-profile design, while the period and modulation index can be tailored to obtain complex shapes [30]. Their high sensitivity to environmental parameters can be compensated or to the contrary, it can be judicious to use it to vary the filter spectral shape using an external command, as a *dynamic gain equalizer*. Such a component was recently proposed, as using the long period grating sensitivity to the outer medium refractive index [31]. The long-period grating is surrounded by two tanks filled with liquids of different indices moving along the grating, one with an index lower than that of the cladding (to tune the wavelength) and a second one with an index higher than that of the cladding (to tune the contrast). The command is electromagnetic.

8. Conclusion

Fiber Bragg gratings are a key technology in telecommunication systems. They are ideal when used in association with fiber lasers, fiber amplifiers or laser diodes. Also, their great design flexibility makes them very attractive for customized applications, such as residual gain equalization or residual chromatic dispersion compensation. Their high spectral efficiency makes them the almost unique solution for very low channel spacing. And even for future high capacity systems requiring dynamic control, such as tunable chromatic dispersion or dynamic gain equalization, IFBGs can play an important role.

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