Acousto-Optic Notch Filter Dynamically Induced in a Chirped Fiber Bragg Grating

Ricardo E. Silva, Martin Becker, Manfred Rothhardt, Hartmut Bartelt and Alexandre A. P. Pohl

***Abstract*— A notch filter acoustically induced in a 1 cm long chirped fiber Bragg grating is experimentally investigated. The notch reflectivity (-5.8 dB to -32 dB) and bandwidth (2.2 nm - 1.3 nm) are tuned by an electrical signal. The reduction of the modulator size and the grating length, compared to previous works with acousto-optic modulation, points to more efficient acousto-optic devices in standard single-mode optical fibers.**

***Index Terms*— acousto-optic devices, fiber Bragg gratings, fiber-optic components.**

I. INTRODUCTION

FIBER BRAGG GRATINGS (FBGS) inscribed in optical fibers and notch filters are suitable for applications as ultra-fast response time all-optical switching, gain equalizers in fiber amplifiers, attenuation filters and band-rejection filters in lasers [1], [2]. Long period gratings (LPGs) inscribed permanently in optical fibers have been employed because their transmission parameters can be tuned by temperature and strain [2]. LPGs can also be obtained by mechanically pressing an optical fiber between a flat plate and a periodically grooved plate [3]. Other approaches to the fabrication of notch filters are implemented by introducing a permanent or dynamic phase-shift in a uniform FBG or in a chirped fiber Bragg grating (CFBG). For example, the phase-shift in the grating structure is introduced by inserting ferrofluids in capillaries of microstructured optical fibers in which the grating is inscribed [4] or by transversally pressing the fiber in a very short region of the grating [5]. Nevertheless, such passive components are not appropriate to handle dynamic variations of the input optical power. Temperature-based techniques employing thermal heating provide an electrical control for dynamically inducing a phase-shift in FBGs [6]. However, the device response time is limited because of the slow material heating/cooling process.

momken n3mel pi-FBG 3n tre2 ferrofluid or b2st5dam temperature laken 2l fiber bys5n w bycool slowly f 2l response time hykon limited

In contrast to these known methods, acousto-optic devices permit a fast control of the modal and elasto-optic properties of optical fibers by electrically tunable acoustic waves. A device normally employed as a notch filter is based on the interaction of flexural acoustic waves and optical modes in a single-mode or multi-mode fiber. Flexural acoustic waves create bends along the fiber inducing a periodic refractive-index perturbation, which couples power of the fundamental mode to higher-order modes. The modal coupling is most efficient if the acoustic period is the same as the beat length between the interacting coupled modes. Although this approach provides relatively high rejection efficiencies (-34 dB) and reasonable switching times (~ 40 μs), the devices in general require high electric power and long fiber lengths to achieve the acousto-optic modulation (devices with 15 cm and 44 cm long fibers, e.g., have been reported) [7], [8]. The use of long interaction lengths also increases the response time of acousto-optic devices because the acoustic wave takes more time to travel along the fiber.

The interaction of acoustic waves with FBGs and LPGs is a good alternative for reducing the size, the switching time (~ 17 μs) and the power consumed by the acousto-optic devices, since the acousto-optic interaction length is reduced to the grating length [9], [10]. In particular, the interaction of flexural waves with long LPGs (~ 5 cm length) allows the dynamic tuning of the grating transmission properties, which is suitable to equalize the gain of optical channels using erbium-doped fiber amplifiers (EDFAs) [10]. However, the inscription of long FBGs or LPGs is limited by the spatial and temporal coherence of interferometric techniques or requires the use of long phase masks or additional equipment to shift the fiber or the laser beam for grating inscription [11]. In addition, in standard single-mode fibers (SMFs), the acoustic power is distributed over the full fiber cross section, which reduces the overlap between the acoustic wave and the grating inscribed in the core. Although cladding-etched fibers or tapered fibers with long gratings enhance the acousto-optic interaction [12], [13], the reduction of the fiber diameter affects its mechanical stability and makes the optical properties more susceptible to surface impurities. One new option to dynamically induce a notch filter is the interaction of longitudinal acoustic waves and chirped fiber Bragg gratings, as illustrated in Fig. 1. An optical mode, with effective index n_{eff} propagating in z direction in a non-perturbed grating of a period varying from Λ_1 to Λ_n, is reflected in different positions in the grating at the wavelength $\lambda_n = 2n_{eff}\Lambda_n$. The grating reflectivity and period variation may be approximated as [14],

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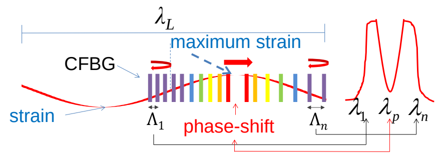

Fig. 1. Illustration of a chirped fiber Bragg grating with the acoustically induced strain and the resulting modulated grating reflection spectrum.

$$\Re(\Lambda(z)) = 1 - \exp\left(\frac{\pi^2 \Delta n_{ac}^2}{2n_{eff}^2 |C|}\right), \quad (1)$$

$$\Lambda_n(z) = \Lambda_0 + C(z - z_0), \quad (2)$$

in which, Δn_{ac}, is the refractive index modulation and, $C = \partial\Lambda(z)/\partial z$, is the chirp parameter being usually expressed in nm/cm. The acoustic wave causes a periodic strain $S(z) = S_0\cos(2\pi fz)$ in the grating with a maximum amplitude S_0. The variation of the grating period caused by the induced strain $S(z)$ and the grating chirp in (2), can be written as [15],

$$\Lambda(z) = \Lambda_n(z)\left[1 + (1 - p_e)S(z)\right], \quad (3)$$

in which, p_e is the elasto-optic constant. Note in (3), if the acoustically induced strain $S(z)$ is null or has a low amplitude, the grating period variation is mainly caused by the grating chirp. However, if the induced strain $S(z)$ achieves a maximum amplitude S_0, the variation of the grating period $\partial\Lambda(z)/\partial z$ along the grating is mainly caused by the acoustic wave, reducing the grating reflectivity in (1). In other words, the acoustic wave induces a dynamic period variation in the grating (phase-shift) at the position of maximum strain S_0, which decreases the grating reflectivity at the optical wavelength λ_p. The acoustic period λ_L is longer than the grating length, as illustrated in Fig. 1. The periodic strain $S(z)$ also changes the adjacent grating periods Λ_n resulting in a rejection filter centered at the notch wavelength λ_p. The notch reflectivity/bandwidth and position of λ_p are tuned by the amplitude and position of the maximum strain S_0 in the grating. For acoustic excitation at frequencies in which the grating supports two or more acoustic wave peaks, more notches can be induced in the grating spectrum, which is suitable for multi-wavelength rejection filters.

The reflectivity modulation of such a chirped fiber Bragg grating by acoustic waves is experimentally investigated in this paper. Changing the electrical power significantly decreases the notch reflectivity compared to results of previous studies [3-5],[7], [10]. The use of the standard fibers also provides better mechanical stability compared to fiber taper and etching techniques. In addition, the notch bandwidth is also tunable. The results indicate strong acousto-optic effects in single-mode fibers, which are attractive for reducing the size and the power consumed by acousto-optic devices.

II. Experimental Setup

Fig. 2 illustrates the setup used for the characterization of the modulated CFBG spectrum. We inscribed a 1 cm long CFBG in the SMF by means of a chirped phase mask interferometer, with two beam interferometry and a lateral nonhomogeneous beam splitter arrangement, as described in [11], [16].

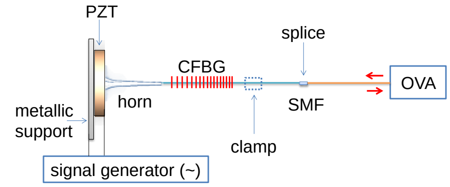

Fig. 2. Illustration of the experimental setup used to characterize the modulated CFBG spectrum.

The modulator is composed of a piezoelectric transducer (PZT) disc of 2 mm thickness and 5 mm diameter, which excites the acoustic waves by means of a solid silica horn of 2.3 cm length (tapered from 1 mm to 125 µm in diameter) and of the SMF with the inscribed CFBG. The whole modulator is 6.9 cm long. The PZT basis is fixed on a metallic support which is connected to an arbitrary signal generator. Conductive glue is used to make the electrical connection between the PZT and the metallic support. By using this technique, conventional soldering methods which may cause undesired loads on the PZT are avoided.

The fiber tip and PZT basis are fixed and the modulator works as a resonant acoustic cavity. The PZT is excited by a 6 V to 10 V sinusoidal signal at the $f = 456$ kHz and $f = 665$ kHz resonances. The grating is characterized by an optical vector analyzer (Luna OVA-5000) with a 1.6 pm wavelength resolution. The SMF of the modulator is spliced to the SMF connecting the OVA by use of an arc-discharge fusion splicer, and the fiber with the grating is spliced to the silica horn.

III. Results and Discussions

Fig. 3(a) shows the CFBG spectrum without acoustic modulation (dashed curve) and with acoustic modulation (solid curves) for the 6 V – 10 V voltage range applied to the PZT at the $f = 456$ kHz resonance. The grating without modulation has the center wavelength at $\lambda_B \sim 1535$ nm, a 3-dB bandwidth of ~10 nm and a maximum reflectivity of ~ 99.9%. No relevant notch effect in the CFBG spectrum is noted for the 1 V – 5 V voltage range of the acousto-optic modulator. However, a notch filter is induced in the spectrum by increasing the voltage. The grating reflectivity is reduced from -5.8 dB to -32 dB by increasing the voltage from 6 V - 10 V. The notch wavelength is $\lambda_p \sim 1534$ nm for the maximum 10 V voltage. The acoustic wavelength $\lambda_a = 1.3$ cm is estimated by considering the longitudinal acoustic velocity in silica as $v = f\lambda_a = 5740$ m/s [17] and the resonance of $f = 456$ kHz. As seen in Fig. 1, the acoustic wavelength $\lambda_a = 1.3$ cm is longer than the 1 cm grating used in this study, which supports only one wave peak. Fig. 3(b) shows the modulated CFBG spectrum at $f = 665$ kHz. Since the estimated acoustic wavelength is $\lambda_a = 0.86$ cm, the 1 cm grating now supports two acoustic wave peaks which induce two notches in the grating spectrum. The notch wavelengths are $\lambda_{p1} \sim 1533.1$ nm and $\lambda_{p2} \sim 1536.6$ nm. The reflectivity in the first notch decreases from -6.8 dB to -25 dB for the 6 V - 10 V voltage range.

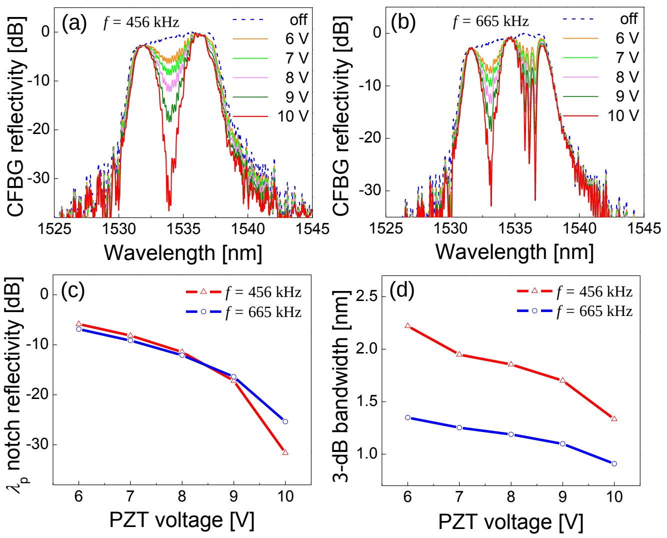

Fig. 3. CFBG spectrum: without acoustic modulation (dashed curve) and with acoustic modulation (solid curves) for the 6 V to 10 V voltage range applied to the PZT at the resonances of (a) $f = 456$ kHz and (b) $f = 665$ kHz. (c) Notch reflectivity and (d) bandwidth responses for the same voltage range.

Although the notch depth and the bandwidth are similar for both notches, a few lobes are noted in the second notch in the longer wavelength range. The acoustic wave probably induces a Fabry-Perot cavity at the position of the maximum strain S_0, which reflects narrowband resonant wavelengths [18]. This effect is observed to be more relevant on the longer wavelength range, in which the grating period becomes longer for increasing z. The resonances may be reduced by choosing proper grating and fiber parameters, by inscribing the grating for a shorter wavelength range or by operating at higher frequencies in which the notch is narrower. Figs. 3(c) and 3(d) show the decrease of the reflectivity and the 3-dB bandwidth with increasing voltage at the notch wavelength λ_p for the resonances at $f = 456$ kHz and $f = 665$ kHz measured in the first notch. The notch bandwidth is reduced from 2.2 nm to 1.3 nm at $f = 456$ kHz and from 1.3 nm to 0.9 nm at $f = 665$ kHz.

Note that in Fig. 3(d), the frequency increase also narrows the bandwidth of the notches in the grating spectrum, because the shorter acoustic wavelength interacts with a shorter region of the grating with the increasing frequency. An increase of the notch depth could be obtained by the application of higher voltages to the PZT (in this study, the voltage is limited to a maximum of 10 V). The tuning of the wavelength λ_p is not investigated because of the discrete behavior of the PZT resonances used in this study [19]. However, by improving the modulator design (e.g. PZT, fiber and grating length), it is expected that variations of the acoustic frequency f (acoustic period) can sweep the maximum strain and the phase-shift along the grating and, consequently, the notch wavelength λ_p.

IV. Conclusion

In summary, an acoustically induced notch filter in a 1 cm chirped FBG is investigated. The notch reflectivity and bandwidth are tuned by an electrical signal. For the best results, a notch reflectivity decrease of -32 dB with a 1.3 nm bandwidth is obtained at a maximum voltage of 10 V. The proposed modulator in a single-mode fiber exhibits considerable rejection efficiency compared to devices based on permanent or dynamic LPGs, since shorter fiber or grating lengths are employed. This is useful to reduce the modulator size, the switching time and the power required to excite the acoustic waves. The use of standard fibers also avoids a cladding reduction by etching or tapering techniques and relaxes the requirements for inscribing long gratings.

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