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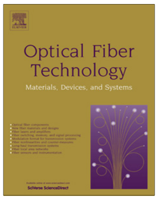

Regular Articles

Numerical and experimental analysis of the modulation of fiber Bragg gratings by low-frequency complex acoustic waves

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ABSTRACT

The acoustically modulated bandwidth of fiber Bragg gratings is simulated and experimentally demonstrated. Finite element and transfer matrix methods are used to investigate a superposition of flexural and longitudinal acoustic waves and the induced complex strain in the grating, for the first time. The results show that the longitudinal strain is suitable to generate a bandwidth-voltage response. The modeling is useful for the design and characterization of acousto-optic modulators, which is attractive for the fast control of several photonic devices.

1. Introduction

Acousto-optic modulation of fiber Bragg gratings (FBGs) has been successfully employed in tunable filters, gain equalizers for erbium-doped fiber amplifiers (EDFAs), Q-switched and mode-locked fiber lasers [1–7]. The sensitivity to temperature and strain of FBGs allows to change the effective index and the grating period and, consequently, the shape of its reflection spectrum. Although temperature-based techniques can be used to modulate the reflectivity of FBGs [8,9], the low sensitivity of the silica thermo-optic coefficient requires high temperatures to produce spectral variations in the nanometer range. Moreover, the device response time is slow because the heating–cooling process in silica presents a high thermal inertia. On the other hand, strain-based techniques provide wider tuning range and faster response time if compared to the temperature-based techniques [10]. In particular, the use of acoustic waves offers higher speed to control the FBG properties employing all-fiber acousto-optic modulators. A coaxial acousto-optic modulator consists of a piezoelectric transducer (PZT), an acoustic horn and an optical fiber with the inscribed grating. The components are axially aligned. Longitudinal acoustic waves excited by such modulators at frequencies in general higher than 600 kHz, induce distinct lobes on both sides of the Bragg wavelength [11–13]. Although the grating modulation with longitudinal waves at higher frequencies has been fully described and understood, the modulation at lower frequencies is clearly marked by the increase of the grating bandwidth, which has not been discussed in detail so far [14]. In addition, previous studies show that the non-uniform deformation of the PZT can simultaneously excite flexural and longitudinal acoustic modes along the fiber, which might induce a superposition of distinct strains along the grating [13,15]. Since the contribution of both waves to the increased bandwidth spectrum is difficult to experimentally characterize, the use of numerical methods is useful to analyze and provide a more accurate information to the design of new acousto-optic devices.

In this paper, we introduce an approach to numerically analyze the strain induced by coupled longitudinal and flexural acoustic waves induced in a FBG. The modulator is operated at a low frequency and the results are validated by simulation and experimental evidences. The results indicate that the net longitudinal strain can be useful to control the grating reflectivity and bandwidth, which are adjusted by the amplitude of an electrical signal.

2. Physical principle

Fig. 1 illustrates the basic principle of this acousto-optic modulation. Fig. 1(a) illustrates an optical mode with effective index n_{eff} being reflected in a non-perturbed grating of period Λ, at the Bragg wavelength $\lambda_B = 2n_{\mathrm{eff}}\Lambda$. Fig. 1(b) illustrates a longitudinal wave

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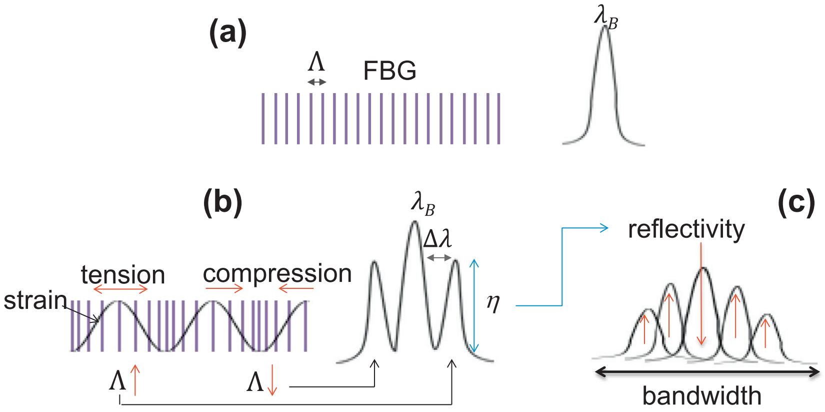

Fig. 1. Fiber Bragg grating and reflection spectra: (a) without modulation, (b) with longitudinal acoustic modulation and the (c) effect on reflectivity and bandwidth.

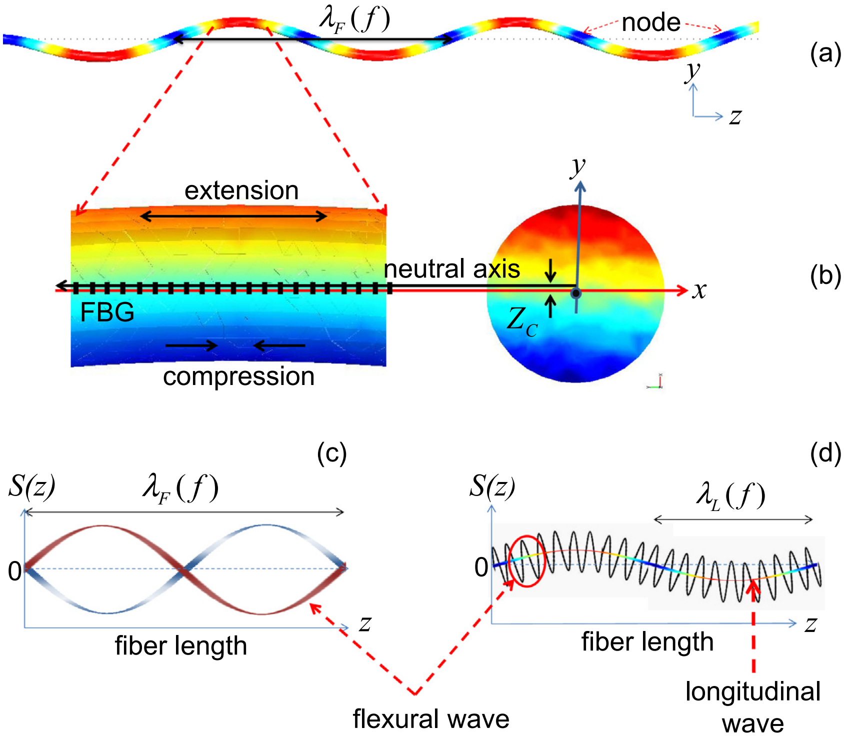

Fig. 2. Illustration of a (a) flexural acoustic wave in the fiber and the (b) induced strain at curvature. (c) Flexural and (d) superposed flexural-longitudinal strains.

inducing a periodic strain along the fiber axis z, which stretches and compresses the grating. The strain modulates the effective index $n_{\text{eff}}(z)$ and the grating period $\Lambda(z)$, inducing lobes on both sides of the Bragg wavelength. The side lobe separation $\Delta\lambda$ can be described as in [11],

$$\Delta\lambda = \frac{f\lambda_B^{\ 2}}{2n_{\text{eff}}\,v_{\text{ext}}} \tag{1}$$

which depends on the acoustic frequency f, the Bragg wavelength λ_B, the acoustic velocity v_{ext} and the effective index n_{eff}. For weak gratings, the m order side lobe λ_m has an effective full width at half maximum (FWHM) bandwidth written as [11],

$$\lambda_{\text{mFWHM}} = \frac{1.39\lambda^2}{\pi L n_{\text{eff}}}. \tag{2}$$

Note in Eq. (1), that the decrease of frequency f reduces the distance between the side lobes, while the reduction of the grating length L in Eq. (2) increases the side lobe bandwidth. For frequencies, grating and fiber parameters, which make the bandwidth of the side lobes larger than the separation between them, the side lobes overlap resulting in a broader grating spectrum. Consequently, the total reflectivity η is reduced if the spectrum bandwidth is broadened, as illustrated in Fig. 1(c).

We consider as "low frequencies" the frequency range in which the side lobes are not resolved in the reflection spectrum or the separation $\Delta\lambda$ between the lobes is small enough to make them overlap. In particular, the increased bandwidth has mainly been observed at frequencies lower than 600 kHz, which satisfy the conditions above, as discussed in Eqs. (1) and (2) [14,16,17].

Fig. 2(a) and (b) illustrate, respectively, the fiber curvatures and the strain distribution $S(z)$ along the z axis, in a step-index single-mode optical fiber (SMF), caused by a flexural acoustic mode of period $\lambda_F(f)$ [18]. Fig. 2(b) shows that the fiber bent in this position causes extension strain (positive) in the upper side and compression strain (negative) in the bottom. The strain is theoretically null at the wave nodes in Fig. 2(a). In this way, the contribution of the