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Fiber-optic Vibration Sensor Based on Bending Characteristics of Long Period Fiber Grating
長周期ファイバグレーティングの屈曲特性を利用した光ファイバ振動センサ

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1. Introduction

Long-period fiber gratings (LPGs) are fiber-optic components having a periodic refractive index of the core with a typical pitch of several hundred micrometers[1]. The periodic structure induces cross-couplings between the core mode and the copropagating cladding modes at certain resonant wavelengths, which results in several attenuation dips in the transmission spectrum. Recently, LPGs have been implemented for use in fiber-optic sensors as well as in fiber-optic communication systems. Since both the wavelength and the transmittance of an attenuation dip are sensitive to temperature, strain, and external refractive index, various types of LPG-based sensors have been proposed. We have previously proposed measurement of vibration of solid using an LPG by adopting an intensity modulation scheme and demonstrated sensitivity enhancement of the vibration detection by using a higher order cladding mode[2]. In the present paper, we examine bending-induced spectral changes of LPGs in terms of the wavelength and transmittance of the attenuation dip. In addition, we construct an intensity-based LPG vibration sensor by using the bending-induced spectral change and demonstrated its highly sensitive operation.

2. Principle

As mentioned above, the core mode can be coupled with the copropagating cladding modes in the LPG so that the LPG has several attenuation dips. Denoting the period of the index modulation of the LPG by Λ, the effective index of refraction for the core mode by n_{co} and that for the m-th order cladding modes coupling with the core mode by $n_{cl}^{(m)}$, the wavelengths of the m-th attenuation dip, $\lambda_p^{(m)}$ is given by[1]

$$\lambda_p^{(m)} = (n_{co} - n_{cl}^{(m)})\ \Lambda\ . \qquad (1)$$

On the other hand, the transmittance of the attenuation dip can be expressed by[1]

$$T^{(m)} = 1 - \sin^2(\kappa^{(m)} L)\ , \qquad (2)$$

where L is the LPG length, $\kappa^{(m)}$ denotes the coupling coefficient between the core mode and the m-th order cladding mode. It is noted that $\kappa^{(m)}$ is in proportion to an overlap integral of the fields of the core and m-th cladding modes. In this situation when the LPG is curved by a bending deformation, the field distribution is also deformed so that the coupling coefficient $\kappa^{(m)}$ as well as the effective indices, n_{co} and $n_{cl}^{(m)}$, are varied. $\lambda_p^{(m)}$ and $T^{(m)}$ therefore changes depend on bending deformation applied to the LPG. It has been reported that much larger spectral change would be obtained for the bending deformation of LPG in contrast to that for axial strain[3,4].

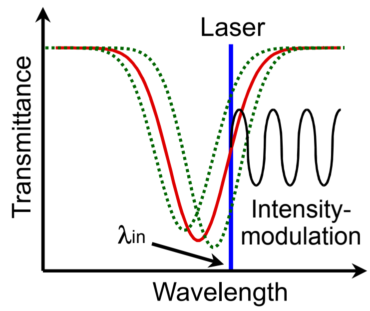

Fig. 1 Conceptual scheme of LPG vibration sensor using intensity modulation scheme.

A conceptual scheme for the operation principle of the LPG vibration sensor is shown in Fig.1; a tunable laser diode (TLD) is used for an optical source of which wavelength λ_{in} is tuned to a transmission spectrum curve of an attenuation dip of an LPG[2]. With reference to the figure, when a flexural vibration is applied to LPG, the transmittance at λ_{in} changes periodically. In this situation, if the vibration-induced curvature variation is small and the wavelength of the laser is chosen to an appropriate operation point, it is expected that the intensity variation is in accordance with the vibration.

3. Experiment and Results

Figure 2 shows a typical transmission spectrum evolution of a LPG of which grating period and grating number are respectively 453 μm and 140. As can be seen from the figure, the two attenuation dips appeared at 1458 and 1602 nm. In order to identify the ordinal number, m, of the cladding mode which contributes respective attenuation dip was estimated; the effective indices of the core and cladding modes,

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n_{co} and $n_{cl}^{(m)}$, were calculated using a step-index approximation[1] and adopting fabrication parameters of photo-sensitized fiber used and the ordinal number for the attenuation dips were determined to be m = 3 for 1458 nm and 4 for 1602 nm. We then measured bending-induced spectral change depending on a curvature of the curved LPG. Figure 3 shows a dependence of the attenuation dip (m = 4) on the bending curvature of the LPG. It is seen from the figure that both the wavelength and depth of the spectral dip are decreased as the bending curvature increases.

After the fundamental characterization of the bending LPG, we applied it to the intensity-based vibration sensing. In the experiment the attenuation dip (m = 4) is chosen and the wavelength of TLD is adjusted to a slope of the dip. As shown in Fig.4, the LPG was curved at a certain curvature and exerted with a flexural vibration using a PZT; a portion of a lead fiber to the LPG was fixed to a rectangular type PZT (140×5×10 mm) with wax glue and driven by a sinusoidal electric signal at its resonant frequency of 10.18 kHz. The transmitted light was directly detected by a photodiode (PD) and its ac component was measured as a sensor output. The sensor output depending on amplitude of the voltage applied to PZT is plotted as shown in Fig. 5. It is seen from the figure that the sensitivities of the sensor outputs depend on the curvature r applied to LPG originally. In the case of ρ = 0 the LPG is not curved; only an axial-strain vibration is applied to the LPG. With a comparison of these results, it is confirmed that the sensitivity of the vibration sensing can be enhanced by adopting the curved LPG; the sensitivity for $\rho = 10\ m^{-1}$ is 17 times larger than that for without bending. The sensitivity is expected to be further enhanced by choosing an appropriate order of the dip and by optimizing the operation point.

4. Conclusion

Bending characteristics of LPGs were investigated for use in an intensity-based fiber-optic vibration sensor, in which TLD used for an optical source with its wavelength tuned to a transmission spectrum curve of the attenuation dip and the partially transmitted light through the LPG was modulated in intensity by applied vibrations. In contrast to the axial strain, it was confirmed that the much larger spectral changes were obtained when bending deformations were applied to the LPG. The LPG vibration sensor was demonstrated by adopting the LPG bending and its highly sensitive operation was performed.

References

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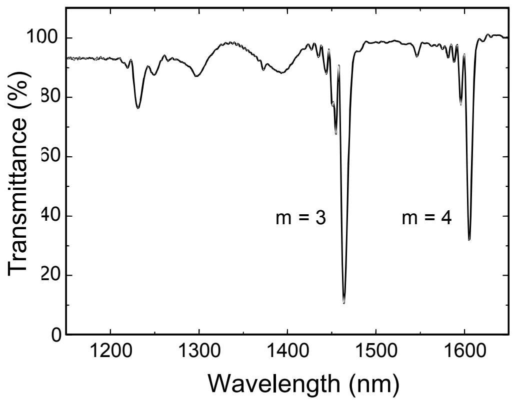

Fig. 2 Transmission spectrum of typical LPG.

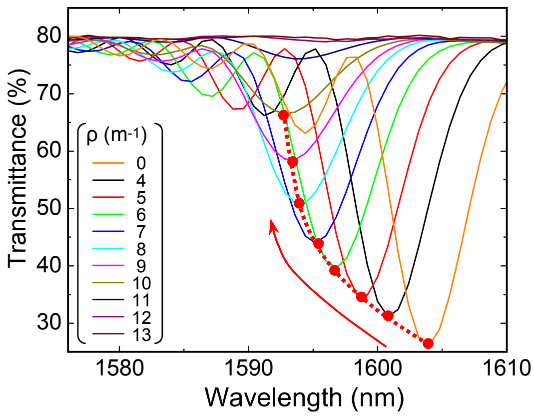

Fig. 3 Bending-induced spectral change (m=4).

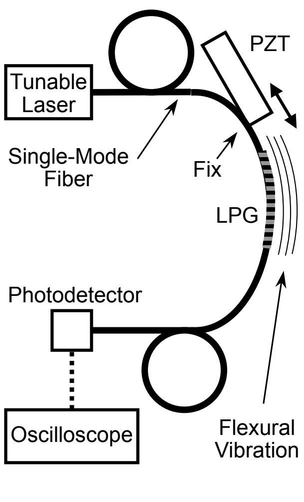

Fig. 4 Experimental setup.

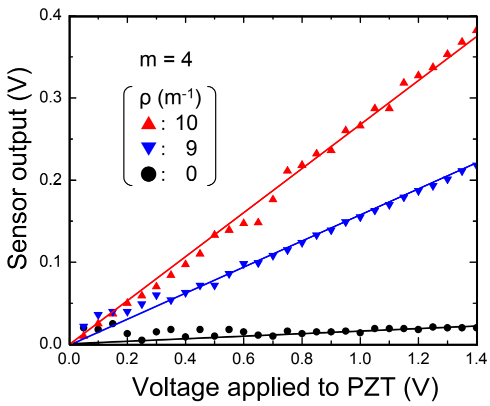

Fig. 5 Sensor outputs as a function of amplitude of voltage applied to PZT..