Mode recoupling between core and cladding modes of cascaded-LPFGs fabricated with heat-shrinkable tube employing a thin confinement layer

Yasuhiro Tsutsumi¹, ², Takahiro Hase¹, Masaharu Ohashi¹, Yuji Miyoshi¹, Hirokazu Kubota¹ and Ikuo Yamashita³
¹ Department of Electrical and Information Systems, Graduate school of engineering, Osaka Prefecture University, 1-1 Gakuen-cho Naka Sakai Osaka 599-8531, Japan
² College of Science and Engineering, Ritsumeikan University, 1-1-1, Nojihigashi, Katsura, Shiga 5258577, Japan
³ Technical Research Center, Kansai Electric Power Inc., 3-11-20, Nakouji, Amagasaki, Hyogo 6610974, Japan
a) TsutsumiYasuhiro@mem.iee.or.jp

Abstract:
Cascaded long period fiber gratings (LPFGs) fabricated with heat-shrinkable tube, screw, and single-mode fiber are proposed herein that employ a thin confinement layer on the bare fiber. The transmittance of a proposed cascaded-LPFG is theoretically and experimentally investigated regarding the cladding mode loss. By employing the confinement layer on the cladding of the proposed LPFGs, mode recoupling between core and cladding modes is successfully induced. Our cascaded-LPFG has potential application for the simple and low-cost optical filters and for the optical sensors monitoring vibration, refractive index, or temperature.

Keywords: mechanically induced long period fiber grating, fiber based Mach-Zehnder interferometer, cladding mode loss, cascaded-LPFG

Classification: Sensing

References

[1] W. J. Stephen and P. T. Ralph, “Optical fibre long-period fibre grating sensors: characteristics and application,” Meas. Sci. Technol., Vol. 14, No. 5, pp. R49-R61, 2003. DOI: 10.1088/0957-0233/14/5/201

[2] S. Nam, C. Zhan, J. Lee, C. Hahn, K. Reichard, P. Ruffin, K.-L. Deng, and S. Yin, “Bend-insensitive ultra short long-period gratings by electric arc method and their applications to harsh environment sensing and communication,” Opt.
Long period fiber gratings (LPFGs) are attractive devices for sensor applications owing to their unique advantages: electro-magnetic immunity, nonexplosiveness, and potential for remote and multiplexing operations [1, 2]. Cascaded-LPFGs that connect two LPFGs in series are promising sensors owing to their high sensitivity for physical parameters such as torsion, temperature, or the refractive index of the surrounding medium [3, 4, 5]. Such high sensitivity for physical parameters arises from a recoupling between core and cladding modes, causing interference between the core and cladding medium [6, 7]. In a cascaded-LPFG, mode coupling between core and cladding modes occurs at the first LPFG, and core and cladding modes are transmitted. At the second LPFG, mode recoupling between cladding and core modes is induced, producing interference between core and cladding modes. Therefore, a cascaded-LPFG acts as a fiber-based Mach–Zehnder interferometer (MZI) [6, 7].

Recently, we proposed a simple fabrication technique for mechanically-induced LPFGs using heat-shrinkable tube [8]. Our LPFGs are fabricated by inserting the fiber between the tube and screw thread [8] and occupying the fiber position where the refractive index periodically changes. As our LPFGs are wrapped with a tube...
and fixed by the tube and screw thread [8]. The LPFG is protected by the tube from the refractive index change of the surrounding medium and the disturbance such as bending of the LPFG. Because of these features, they cannot be used as sensors for measuring the surrounding refractive index and the bending of the LPFG. To overcome these problems, a fiber-based MZI containing cascaded-LPFGs would be effective because the transmittance is sensitive towards the changes in physical parameters at the interval fiber between the LPFGs [9]. A cascaded-LPFG of fiber-based MZI accomplishes all those using our LPFGs protected by the tube. It can be used as the sensor which doesn’t detect the changes in the physical parameters at the LPFGs, but in the fiber between the LPFGs. However, mode recoupling between cladding and core modes did not occur when our LPFGs fabricated via heat-shrinkable tube were cascaded [10].

In this study, we propose a simple structure of cascaded-LPFGs fabricated with heat-shrinkable tube that causes mode recoupling between core and cladding modes. To reduce the cladding mode loss, a thin metallic layer is employed. Using a transfer-matrix model, we investigate the transmittance of the cascaded-LPFG, focusing on the cladding mode loss at the LPFG [9], and clarify that the mode recoupling of the conventional cascaded-LPFG fabricated with heat-shrinkable tube [10] does not occurred due to high cladding mode losses.

2 Theory

Fig. 1 shows the structure of a cascaded-LPFG that connects two LPFGs with the same parameters in series.

The field amplitudes \( A_c \) and \( A_d \) which correspond to respective the core mode and cladding mode can be written as follows by using the transfer matrix \( F_L \) of the LPFG and the transfer matrix \( F_F \) of the fiber between the LPFGs based on the transfer matrix analysis [9].

\[
\begin{bmatrix}
    A_c \\
    A_d
\end{bmatrix} = F_L F_F \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]  

(1)

The transfer matrix \( F_L \) of the LPFG is expressed as follows [9].

\[
F_L = \begin{bmatrix}
  \cos(\gamma_c L) + i \frac{\delta}{\gamma_c} \sin(\gamma_c L) & i \frac{\kappa}{\gamma_c} \sin(\gamma_c L) \\
  i \frac{\kappa}{\gamma_c} \sin(\gamma_c L) & \cos(\gamma_c L) - i \frac{\delta}{\gamma_c} \sin(\gamma_c L)
\end{bmatrix}
\]  

(2)

![Fig. 1. Structure of a cascaded-LPFG fabricated with heat-shrinkable tube and an aluminum foil layer.](image-url)
\[
\delta = \pi \Delta n_{\text{eff}} \left( \frac{1}{\lambda} - \frac{1}{\lambda_p} \right) \equiv \frac{\pi}{\Lambda} \left( \frac{1}{\lambda} - \frac{1}{\lambda_p} \right), \quad \gamma_c = \sqrt{\kappa^2 + \delta^2},
\]

where \( L \) and \( \Lambda \) denote the length and pitch of the LPFG, respectively. \( \Delta n_{\text{eff}} \) gives the effective index difference between core and cladding modes. \( \lambda_p \) is a resonance wavelength of the LPFG. \( \kappa \) and \( \delta \) are the coupling coefficient and detuning factor of the LPFG, respectively [9].

For LPFGs fabricated with heat-shrinkable tube, the propagation losses of cladding modes occur due to the microbending. Moreover, when the refractive index of the material surrounding the cladding is sufficiently greater than that of the cladding, then the propagation losses of cladding modes occur due to coupling with leaky modes [6, 7].

To express the cladding mode loss in the LPFG, the transfer matrix of the LPFG with cladding mode loss is defined as follows.

\[
F_L = \begin{bmatrix}
\cos(\gamma_c L) + i \frac{\delta}{\gamma_c} \sin(\gamma_c L) & i \frac{\kappa}{\gamma_c} \sin(\gamma_c L) \\
-i \frac{\kappa}{\gamma_c} \sin(\gamma_c L) & e^{i \alpha} \left[ \cos(\gamma_c L) - i \frac{\delta}{\gamma_c} \sin(\gamma_c L) \right]
\end{bmatrix},
\]

where \( \alpha \) represents the cladding mode loss in the LPFG.

The transfer matrix of the fiber between the LPFGs is expressed as follows.

\[
F_D = \begin{bmatrix}
\exp \left( \frac{2 \pi \Delta n_{\text{eff}}}{\lambda} D \right) & 0 \\
0 & \exp \left( -\frac{2 \pi \Delta n_{\text{eff}}}{\lambda} D \right)
\end{bmatrix},
\]

where \( D \) is the fiber length between the LPFGs.

The transmittance \( T \) of the cascaded-LPFG can be calculated by the following equation.

\[
T = |A_{\text{in}}|^2
\]

We calculated the transmittance of the cascaded-LPFG with a length \( L \) of 5.5 cm, a grating period \( \Lambda \) of 0.7 mm, and a resonance wavelength \( \lambda_p \) of 1607 nm.

![Fig. 2. Calculated transmittance of cascaded-LPFGs for various distances \( D \) (a) \( D = 0 \) cm, (b) \( D = 15 \) cm, (c) \( D = 30 \) cm, and (d) \( D = 50 \) cm. Calculated transmittance of cascaded-LPFGs with \( D = 50 \) cm for various values \( \alpha \), (e) \( \alpha = 0.5 \) Np, (f) \( \alpha = 1.0 \) Np, (g) \( \alpha = 1.5 \) Np, and (h) \( \alpha = 2.0 \) Np.](image)
using the above model for the case of no attenuation loss in the fiber between the LPFGs.

Figs. 2 (a)–(d) show the transmittance of the cascaded-LPFG with no cladding mode loss \( \alpha = 0 \) for various distances \( D \) between the LPFGs. To simplify the calculations, we ignored the wavelength dependence of the coupling coefficient \( \kappa \) and the effective index difference \( \Delta n_{eff} \) between core and cladding modes, and we set \( \kappa \) at 19 and \( \Delta n_{eff} \) at 0.0022956 considering experimental results [8]. We found that when the distance \( D \) is 0, the transmittance of the cascaded-LPFG equals that of a united-LPFG which is connected the LPFGs with a length of \( L \). The wavelength spacing between the adjacent peaks of the cascaded-LPFG decreases as the distance \( D \) increases, and therefore the attenuation bandwidths decrease as the distance \( D \) increases.

We also calculated the transmittance of the cascaded-LPFG for various values \( \alpha \) of cladding mode loss, as shown in Figs. 2 (e)–(h). The cladding mode loss \( \alpha \) (Np) was set to each of four values: 0.5, 1.0, 1.5, and 2.0. These correspond to 2.17 dB, 4.34 dB, 6.51 dB, and 8.69 dB, respectively. In the simulations, we set the distance \( D \) between LPFGs at 50 cm. We found that the fringe visibility [6, 9] decreases as the cladding mode loss increases. For high cladding mode losses, beats caused by the interference between core and cladding modes could not be observed. It is seen from Figs. 2(a) and (e)–(h) that the attenuation bandwidth of cascaded-LPFGs broadens compared with a united-LPFG as the cladding mode loss increases. The measured spectrum of the united-LPFG fabricated with a heat-shrinkable tube shows the similar one calculated for the high cladding mode loss [8, 10]. Therefore, we clarified that the mode recoupling of the conventional cascaded-LPFG fabricated with the heat-shrinkable tube cannot occur due to the high cladding mode loss, and that the cladding mode loss is an important factor for controlling the transmittance of the cascaded-LPFG.

### 3 Experimental results

As illustrated in Fig. 1, to confine the cladding mode into the fiber, the bare fiber was covered with a thin layer of aluminum foil which reduce the microbending loss and change the refractive index of the surroundings. We fabricated the cascaded-LPFG in the following way. First, we put a bare optical fiber on a sheet of aluminum foil, then wrapped a screw thread with the foil. We inserted the wrapped thread and fiber into the heat-shrinkable tube and heated the tube. By heating the tube, the tube shrinks and the fiber contacts the thread. After cooling

![Fig. 3. Transmittance of cascaded-LPFGs (a) with an Al foil layer (Proposed), (b) without an Al foil layer (Conventional)](image-url)
the tube to room temperature, the periodic refractive index modulation was induced by the photo-elastic effect, thereby creating a LPFG [8]. In the same manner, we fabricated a 2nd-LPFG with aluminum foil at a distance $D$ from the 1st-LPFG.

The cascaded-LPFG was fabricated with the heat-shrinkable tube (Hagitech-NF040), standard-optical telecommunication fibers (ITU-T. G.652), aluminum foil of thickness 75 μm, and screw threads with a pitch $\lambda$ of 0.7 mm and length $L$ of 5.5 cm. The distance $D$ between the LPFGs was 50 cm. The conventional cascaded-LPFG with high loss of cladding mode [8] was fabricated as a reference sample using the same components but excluding the aluminum foil. Figs. 3(a) and (b) show the measured transmittances of the cascaded-LPFGs with and without an aluminum foil layer, respectively. The measured transmittance of the cascaded-LPFG with aluminum foil showed a lot of narrow attenuation bandwidth. The measured spectrum in Fig. 3(a) was in good agreement with the simulation one for the low cladding mode loss in Fig. 2 (g). In contrast, the transmittance of the cascaded-LPFG without the aluminum foil shows a broader attenuation bandwidth. The measured spectrum in Fig. 3(b) was in good agreement with the simulation one for the high cladding mode loss in Fig. 2 (h). It is found that the confinement layer is effective for reducing the cladding mode loss. However, the fringe visibility of the cascaded-LPFG with the aluminum foil is small, so the cladding mode loss is slightly higher. This slightly higher loss is attributed to an imperfect interface surrounding cladding, which may cause the scattering loss [6]. In addition, since we wrapped only a part of the fiber with aluminum foil, losses may also have arisen from the part of the fiber in contact with the air and screw thread inside the tube. The fringe visibility could be improved by optimizing the structure of the confinement layer.

4 Conclusions

We proposed a simple fabrication method for a cascaded-LPFG fabricated with heat-shrinkable tube and a thin confinement layer of aluminum foil. We investigated the transmittance of the cascaded-LPFG as a function of the cladding mode loss using a transfer matrix analysis. We clarified from our simulation results that the attenuation bandwidth of the cascaded-LPFG can be determined by the cladding mode loss. Considering the similarity of the spectra, we also clarified that the mode recoupling of the conventional cascaded-LPFG cannot occur due to the high-cladding mode losses. We confirmed experimentally that the proposed structure of the cascaded-LPFG employing a thin confinement layer on the cladding is effective for confining the cladding mode into the fiber and for inducing the mode recoupling between the core and cladding modes. As the result, controllability of transmission of cascaded-LPFG are improved significantly.

Cascaded LPFGs fabricated with a heat-shrinkable tube have potential uses for the simple and low-cost optical filters and for the optical sensors monitoring vibration, refractive index, or temperature.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 16K06307.