Tunable Loss Filter Based on Metal-Coated Long-Period Fiber Grating

D. M. Costantini, C. A. P. Muller, S. A. Vasiliev, H. G. Limberger, and R. P. Salathé

***Abstract*— An all-fiber electrically tunable loss filter that is based on photoinduced long-period grating coated by Ti–Pt metal coating was developed and investigated. Maximum wavelength tuning of 11 nm with an applied power of 0.67 W was achieved for the HE_{17} cladding mode resonance peak.**

***Index Terms*—Fiber gratings, metal coatings, optical fiber devices, optical fibers.**

I. INTRODUCTION

LOSS filters based on long-period fiber gratings (LPG) are of great interest for applications in optical fiber systems. Such filters are ideal for gain flattening of erbium-doped fiber amplifiers and other applications requiring spectral control [1]. Greater flexibility and improved performance are guaranteed by trimming [2] or tuning [3] of the LPG resonance wavelength. Trimming permits a postfabrication positioning of the filter resonance peak, while tuning allows for dynamic spectral shaping. The tuning of the grating resonance wavelengths can be achieved by applying a strain, by bending or by heating the fiber section that contains the grating [1], [3]. Recently, we demonstrated that Joule heating can be used to efficiently tune and modulate the reflection spectrum of a fiber Bragg grating (FBG) coated with a resistive radially symmetrical layer [4], [5]. Here, we report on an all-fiber tunable loss filter that is based on an LPG and a thin-metal coating. The metal layer allows electrical tuning and modulation of the resonance wavelengths. Spectral changes and response time of the device are investigated and discussed.

II. THEORY

An LPG consists of a periodic variation of the core refractive index along the fiber, with a typical period between 50 and 500 μm. The operation of a LPG is based on the coupling between the fundamental core mode HE_{11} and the cladding modes $HE_{1m}\,(m = 2, 3, \cdots)$. The coupling between the modes takes place if the phase matching condition is fulfilled [1]:

$$\lambda_{1m} = \left(n_{11}^{\text{eff}} - n_{1m}^{\text{eff}}\right)\Lambda = \Delta n_{1m}^{\text{eff}}\Lambda \tag{1}$$

where λ_{1m} is the resonance wavelength corresponding to the cladding mode HE_{1m}, Λ is the grating period, n_{11}^{eff} and n_{1m}^{eff} are the effective refractive indices of the fundamental and cladding modes, respectively. Thus, the transmission spectrum of a LPG exhibits several resonance loss peaks, corresponding to different couplings.

The relative shift in the HE_{1m} resonance peak wavelength induced by a temperature change ΔT is given by [6]

$$\frac{\Delta\lambda_{1m}}{\lambda_{1m}} = \frac{\dfrac{1}{\Delta n_{1m}^{\text{eff}}}\dfrac{\partial \Delta n_{1m}^{\text{eff}}}{\partial T} + \dfrac{1}{\Lambda}\dfrac{d\Lambda}{dT}}{1 - \Lambda\dfrac{\partial \Delta n_{1m}^{\text{eff}}}{\partial \lambda}}\Delta T = \zeta_{1m}\Delta T. \tag{2}$$

The shift is mainly defined by the core-cladding refractive index difference (first term in the numerator) and the waveguiding properties of the fiber (denominator). All different contributions to the temperature sensitivity of the LPG resonance wavelengths can be expressed by a temperature coefficient ζ_{1m}, which depends on the cladding mode number.

For a metal-coated fiber grating, the temperature within the fiber changes in accordance with the heat generated by the electric current, which flows through the surface coating. This results in a change of the resonance peak wavelength [4], [5], [7]. The temperature distribution in the coated fiber is governed by diffusion of heat into the fiber as well as heat loss at the surface due to conduction of heat to electrical contacts and fiber holder, and free convection in the surrounding air. In a first approximation, all heat loss mechanisms can be lumped into a linear coefficient H [8]. At thermal equilibrium the heat equation has the form

$$P_{el} = HL\Delta T \tag{3}$$

where P_{el} is the applied electrical power, L is the coating length, and ΔT is the temperature change within the fiber. If we assume that the thin metal coating does not induce any strain on the LPG, $\Delta\lambda_{1m}/\lambda_{1m}$ can be expressed as a linear function of the applied electrical power

$$\frac{\Delta\lambda_{1m}}{\lambda_{1m}} = \frac{\zeta_{1m}}{HL}P_{el}. \tag{4}$$

For a step increase of electrical power P_{el} to the conductive coating, the temperature $T(t)$ increases exponentially with a time constant $\tau = C/H$ [8], where C is the effective thermal mass per unit length. The time constant τ for metal-coated fiber systems is less than one second [7]–[9].

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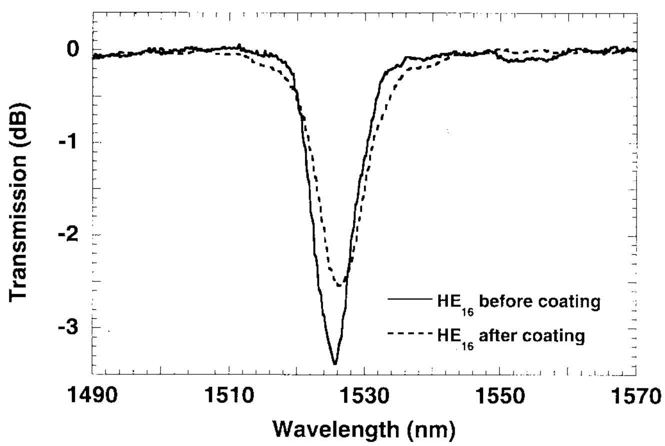

Fig. 1. LPG transmission spectra for HE_{16} mode coupling before (solid curve) and after (dashed curve) the deposition of the thin-film metal coating.

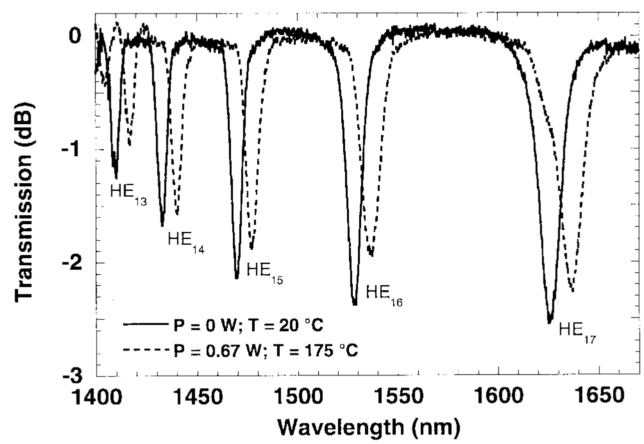

Fig. 2. Transmission spectra of the LPG at room temperature without electrical heating (solid curve) and for an applied power of 0.67 W (dashed curve).

III. Results and Discussion

An LPG was written in a single-mode germanosilicate fiber. The fiber has a step-index profile, a concentration of 12 mol.% GeO_2 in the core, and core and cladding diameters of 3.5 and 125 μm, respectively. The fiber was irradiated by excimer laser light through an amplitude mask with a period of 300 μm. The length of the grating was about 20 mm. A tungsten lamp, a monochromator, and lock-in detection were used to measure the grating spectra in a spectral range from 1.4 to 1.65 μm with a resolution of 0.5 nm. The HE_{16} resonance in the range 1490–1580 nm was characterized with a tunable semiconductor laser, using a wavelength step of 0.2 nm.

After laser irradiation, the fiber section hosting the LPG was cut to 19 cm length and any remaining polymer coating was stripped off. DC magnetron sputtering was used to deposit on the fiber a radially symmetric coating of platinum with a thickness of 100–300 nm. Titanium coating of about 10-nm thickness was deposited beneath the Pt layer to improve the adhesion between Pt and silica. The Ti/Pt coating covered entirely the LPG and had a length of 62 mm.

The metal-coated optical fiber was placed in a V-groove of a Teflon substrate to minimize bending of the fiber. Four copper electrodes assured the electrical contact by means of a small pressure on the coated fiber. Electrical connections were placed at a distance of 29 mm and a total resistance of 54 Ω was measured at the temperature of 20 °C.

Fig. 1 shows the transmission spectrum of the HE_{16} cladding mode resonance before and after deposition of the metal layer. Before coating, the peak shows a transmission loss of 46% and a 3-dB bandwidth of 7.6 nm. The presence of the metal layer on the fiber surface shifted the resonance peak by 1 nm toward longer wavelengths as compared to air, whereas the bandwidth increased by 1 nm and the transmission loss decreased by 10%. The main conclusions that can be drawn are 1) the coupled cladding mode is guided due to Fresnel reflection at the silica/metal interface; 2) the cladding mode is lossy, leading to a reduction of the coupling between core and cladding modes and to an increase of the bandwidth; and 3) the shift of the resonance peak toward longer wavelengths is governed by both the real and imaginary part of the metal refractive index. Its explanation would need a rigorous solution of the waveguide equation, which is beyond the scope of this letter.

It is well known that the penetration depth of electromagnetic waves into a metal is a small fraction of the wavelength [10]. Therefore the electric field of the cladding mode should be completely screened by the Ti/Pt deposited on the LPG. The sensitivity of the metal-coated long-period grating to the refractive index of an external medium was checked by immersing the coated fiber in liquids with different refractive indices. As expected no spectral changes were observed in contrary to a bare fiber grating that is strongly sensitive to the external refractive index [1]. It follows that metal coatings can be efficiently used for protection of LPG's from the influence of external medium, e.g., packaging purposes.

Fig. 2 shows the transmission spectrum of the device without electrical heating at the temperature of 20 °C (solid line) and for an applied power of 0.67 W (dashed curve). Five resonance peaks corresponding to the coupling of the fundamental HE_{11} mode to the $HE_{1m}\,(m = 3, \cdots, 7)$ cladding modes are displayed. During heating the loss peaks shifted to higher wavelengths. Small changes of the spectral shape that are probably due to a nonuniform temperature distribution along the grating length have been observed.

Fig. 3 represents the dependence of the resonance wavelength shift of the cladding modes on the electrical power. The wavelength shift is linear and increases with mode order for the observed cladding modes. A maximum shift of 11 nm was achieved for the HE_{17} mode with an applied power of 0.67 W. This gives a tuning efficiency of 16.4 nm/W. To obtain the coefficients ζ_{1m} we determined the temperature rise ΔT by measuring the resistivity change induced by the applied power. The temperature dependence of the resistivity of the Ti–Pt layer is 2.3×10^{-3} K^{-1} [7]. The values of ζ_{1m} are summarized in Table I. Using (3) a heat loss coefficient H of 15×10^{-2} $W{\cdot}K^{-1}m^{-1}$ is obtained. If the fiber is surrounded by air the tuning efficiency increases due to the lower heat loss and a coefficient H of 5×10^{-2} $W{\cdot}K^{-1}m^{-1}$ has been measured.

To measure the time response of the all-fiber tunable loss filter the output wavelength of a tunable laser was placed

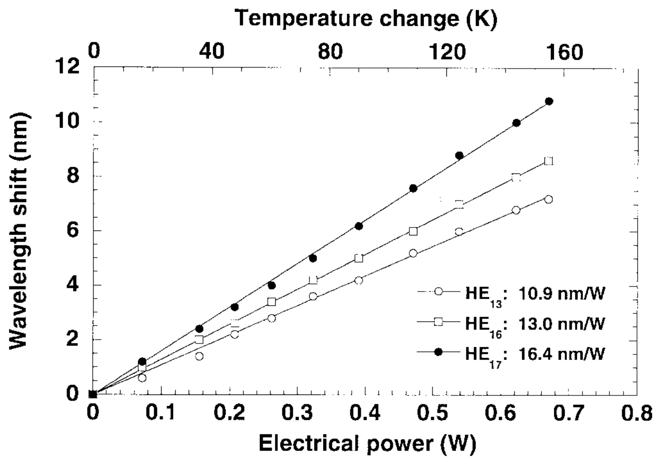

Fig. 3. Dependence of the wavelength shift of resonance peaks on the applied electrical power.

TABLE I
TEMPERATURE SENSITIVITY OF CLADDING MODE RESONANCES

m	3	4	5	6	7
λ_m (nm)	1409.6	1433.0	1469.8	1528.2	1626.0
ζ_{1m} (10^{-5} K^{-1})	3.3 ± 0.17	3.3 ± 0.17	3.4 ± 0.17	3.6 ± 0.18	4.2 ± 0.21

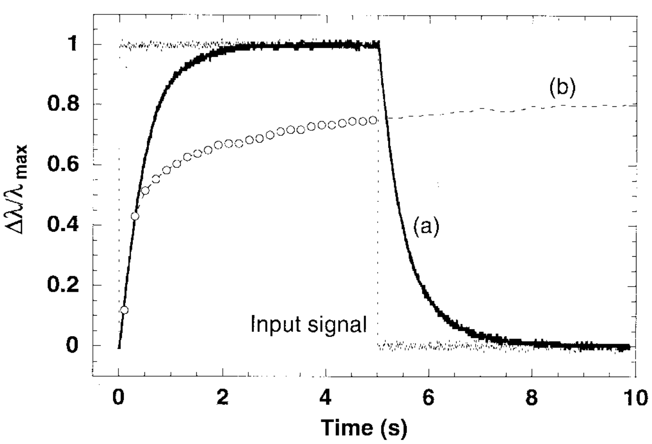

Fig. 4. Response of the tunable filter to a rectangular electrical signal. (a) Fiber surrounded by air. (b) Fiber placed on Teflon substrate.

in the linear region of the low-wavelength side of the sixth-order peak and rectangular electrical signals were applied. Heat diffusion into the fiber, convection in the surrounding air, and heat diffusion into the Teflon substrate determines the time response. The heat diffusion into the fiber is very fast and on the order of a few milliseconds [8]. The time to thermal equilibrium is therefore governed by heat loss. Fig. 4 shows the response of the filter for two different situations. First, if the fiber is surrounded by air and a 5-s rectangular power pulse was applied (dotted line). In this case, the heat loss is mainly due to convection and the normalized wavelength shift follows an exponential law with a time constant τ of about 0.5 s (solid line). Second, if the fiber is placed on the Teflon substrate, the transient process is governed by convection and heat diffusion into the substrate. Applying a much longer power pulse (not shown in Fig. 4), we now measured a time constant of about 70 s (circles and dashed line).

IV. CONCLUSION

We presented an all-fiber tunable loss filter based on a LPG and Ti–Pt metal coating. The metal coating allows electrical tuning and modulation of the resonance wavelengths, while making the LPG filter insensitive to the surrounding medium. A maximum wavelength shift of 11 nm and a linear tuning efficiency of 16.4 nm/W were obtained for the seventh-order mode. The wavelength shift of the resonance peaks was linear with the applied electrical power and no strong changes of the grating's spectral shape were observed. The time response of the filter was measured. Time constants of 0.5 and of about 70 s were obtained for situations where the fiber was surrounded by air or placed on a Teflon substrate. The component developed is ideal for fine tuning, modulation and wavelength stabilization of LPG filters. Low power consumption and small size are important characteristics of this novel grating component.

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