Fiber optic hot-wire flowmeter based on a metallic coated hybrid long period grating/fiber Bragg grating structure

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In this work an all-optical hot-wire flowmeter based on a silver coated fiber combining a long period grating and a fiber Bragg grating (FBG) structure is proposed. Light from a pump laser at 1480 nm propagating down the fiber is coupled by the long period grating into the fiber cladding and is absorbed by the silver coating deposited on the fiber surface over the Bragg grating structure. This absorption acts like a hot wire raising the fiber temperature locally, which is effectively detected by the FBG resonance shift. The temperature increase depends on the flow speed of the surrounding air, which has the effect of cooling the fiber. It is demonstrated that the Bragg wavelength shift can be related to the flow speed. A flow speed resolution of 0.08 m/s is achieved using this new configuration.

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1. Introduction

Flow measurement is important for many applications in chemical engineering, in the energy and aerospace industries, and in medical equipment technology. Several approaches have been employed for mass flow measurement, including time of flight measurement, differential pressure measurement, and heat transfer [1–4]. The installation of a large number of flow sensors is currently very difficult and expensive. One type of conventional single point flow sensor is the so-called hot-wire anemometer, in which a high resistance electrical wire is heated by a constant current. Air flow cools the wire down depending on the flow velocity, as the resulting temperature decrease is a measure of the flow level.

Flow measurement using optical fiber devices has also been reported based on fiber bending Raman backscattering [5] or using resonant shift fiber Bragg gratings (FBGs) [6,7]. The FBG spectral shift transducing mechanisms include mechanical stretching, bending, electrical heating, and the piezoelectric effect [8,9]. All of these tuning mechanisms require labor-intense packaging and external energy that is supplied through electrical cables. The additional packaging and electrical cabling can be easily eliminated using fiber components, which reveal other inherent advantages, such as low cost, multiplexing, long lifetime, compactness, immunity to electromagnetic fields, and capability of working in hostile environments.

Recently, some researchers have proposed all-optical flowmeter sensors. In these configurations the FBG resonance is tuned by a high power laser

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radiation propagating in the fiber [10]. For this purpose a silver thin film is coated around all of the FBGs having a linear expansion coefficient larger than that of silica. The optical power induced spectral shift of the FBG resonance is dependent on absorption of radiation in the film, leading to a temperature increase in the fiber [11]. This mechanism requires light to be coupled into the cladding of the single-mode fiber to be effectively absorbed by the film. Typically, to couple the laser light into the cladding of the single-mode fiber, a section of multimode fiber spliced in the grating vicinity is used. This process can introduce substantial losses into the system due to mismatching characteristics of the two fibers, thus effectively reducing the multiplexing capability.

In this work a new lossless process to increase the temperature of the thin film by coupling radiation to cladding modes using a long period grating (LPG) is proposed. An LPG is used to couple radiation from the core mode to the cladding modes, providing lossless coupling to the cladding without compromising the fiber's physical integrity. This configuration has the advantage of enabling an optical flowmeter entirely in single-mode fiber, reducing the losses in the system, thus enabling its effective multiplexing.

2. Experimental Setup

The experimental setup is presented in Fig. 1. A broadband source (BBS) centered at 1550 nm is used to illuminate a sensing head formed by an LPG followed by an FBG with a uniform silver thin-film overcoat. The separation between the LPG and the FBG is 10 mm. The silver thin-film overcoat was prepared by dip coating the section containing the FBG in a silver nitrate based solution. The film covers a length of 15 mm and has an approximate thickness of 200 nm. A 3 dB optical coupler is used to interrogate the sensing head in reflection, and a fused WDM coupler (1480/1550) is spliced between the 3 dB optical coupler and the sensing head to inject the pump laser with 400 mW output power at 1480 nm. The FBG structure was fabricated in the Corning SMF-28 fiber with around 70% of reflection and a central wavelength of 1514 nm. A silver thin film coats the FBG in order to absorb the radiation coupled to the cladding. To couple the pumping laser diode radiation to the cladding, an LPG was inscribed in the same fiber prior to the FBG location. The LPG was fabricated using the electric-arc technique [12]. The period of the refractive index modulation was set to 385 μm in order to produce a resonance wavelength at approximately 1480 nm, corresponding to the LP_{15} cladding mode that matched the diode laser central wavelength (Fig. 2). The heat created by the absorption of radiation increases the temperature in the region of the FBG, causing a shift of its resonance, which allows the flow measurement. The reflection spectrum of the FBG was monitored with an optical spectrum analyzer (OSA).

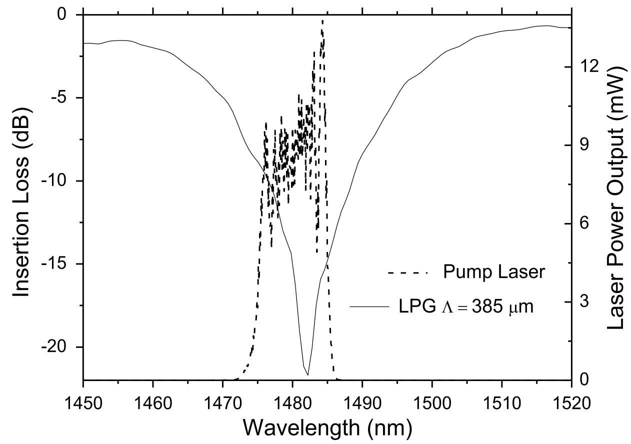


Fig. 2. Spectra of the pump laser emission and the LPG resonance.

To test the sensor head performance as a flow sensor, a test chamber with two entrances was built. A reference flowmeter was inserted in the input to measure the real flow in the test chamber. The sensor head was kept in the chamber under constant strain to avoid cross sensitivity.

3. Results and Discussion

To evaluate the flowmeter concept, several tests were performed. The first step was to observe the spectral shift of the FBG resonance when the LPG, acting as a coupling element, was irradiated with pump laser. Figure 3 shows the evolution of the FBG spectrum when it was heated by the 1480 nm laser radiation using an LPG to couple radiation to the cladding. Because the thermal mass of the grating is low,

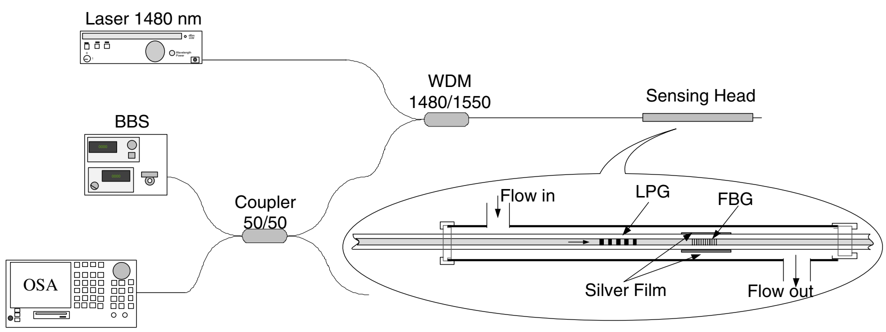


Fig. 1. Experimental setup with the details of the sensing head.

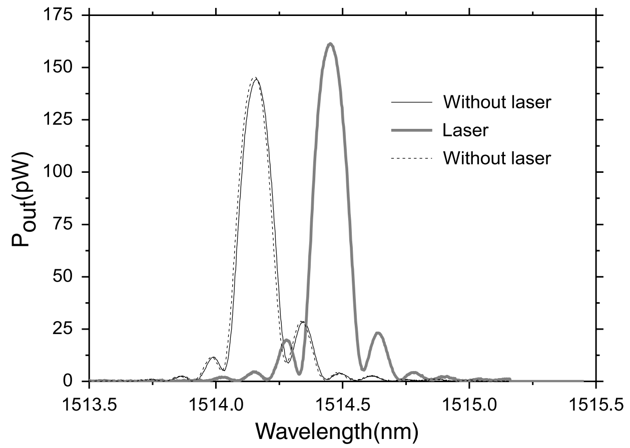


Fig. 3. Bragg grating spectral response when the heating laser radiation (1480 nm) was turned on and off.

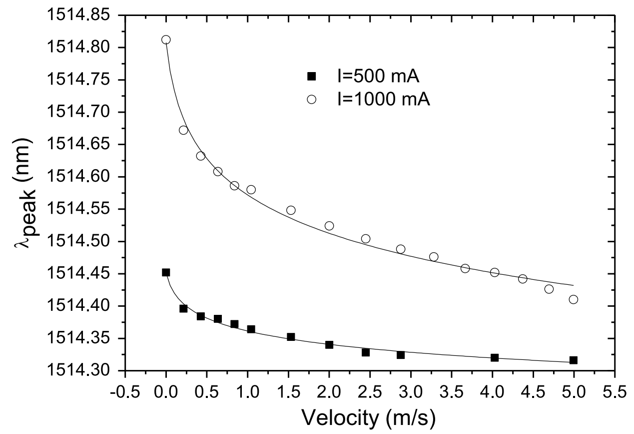
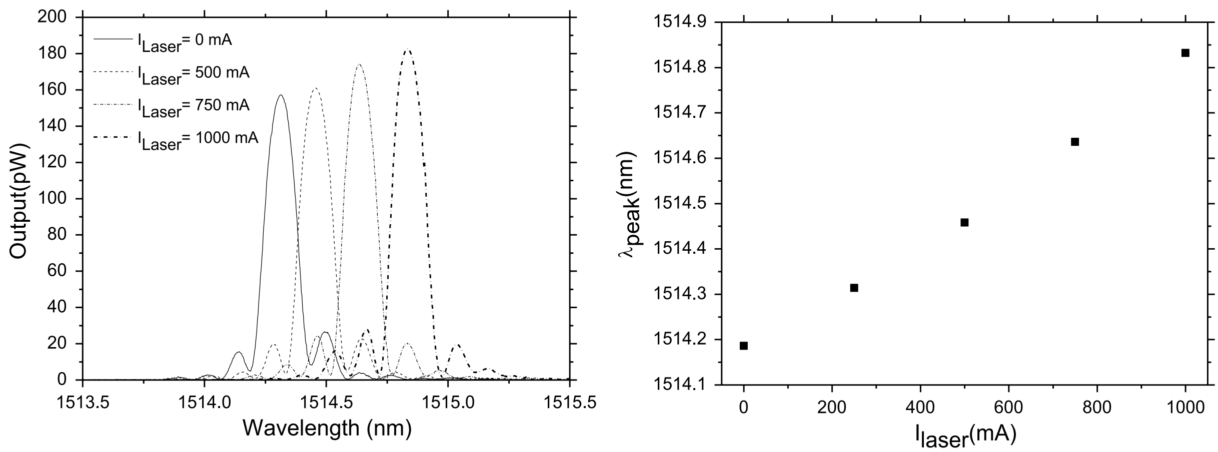


Fig. 5. FBG resonance wavelength shift when the sensing head is subjected to a range of flows speeds for two distinct laser currents (500 and 1000 mA).

the absorption of laser radiation by the silver coating effectively raises its temperature and shifts the resonance wavelength. Figure 3 also illustrates that when the laser is turned off, the resonance of the FBG returns to its initial position.

Figure 4(a) presents the FBG spectral response for different values of the pump laser drive current. It shows that increasing the input pump power of the laser leads to a deviation of the FBG resonance to longer wavelengths. The small difference in the reflection power is due to the fact that the FBG is located at one edge of the slope of the LPG. Thus, proper design of the sensing head may allow intensity monitoring instead of wavelength, leading to cost savings. The change in the FBG resonance peak wavelength as a function of the laser current is shown in Fig. 4(b). The redshift of the FBG resonance with the laser current is approximately linear and demonstrates that the increase of power in the cladding also causes an increase of the power absorbed by the silver thin film, with the consequent increase of the fiber temperature in the FBG region.

The heated FBG is very sensitive to surrounding air flow disturbances. Figure 5 shows the wavelength of the FBG resonance peak as a function of the air velocity in the chamber for two distinct values of the power of the laser diode. It appears that the wavelength of the FBG resonance tends to closely follow a function of simple exponential decay with the velocity of air flow inside the test chamber. The introduction of the air flow increases the rate of removal of heat from the FBG device and reduces the temperature of the FBG sensor. This change in resonance wavelength is more pronounced for lower flow speeds. Nevertheless, due to limited resolution of the flowmeter used for calibration, this range could not be explored in more detail. This dependence may be explained as follows: in stationary conditions all the energy reaching the film is removed by convection according to the Newton's law of cooling. This equation states that the heat removed by convection is proportional to the temperature difference between the film and the fluid multiplied by the convection heat transfer coefficient. On the other hand, this



(a) (b)

Fig. 4. (a) Spectral response of the FBG and (b) its resonance peak shift for different driving currents of the pump laser.

coefficient is proportional to a power, less than unity, of the fluid velocity, through the relation between Nusselt's number and Reynolds's number for flow "across" a cylinder [13]. Therefore, the convection heat transfer coefficient increases faster for lower speeds, and since the energy reaching the film remains constant over time, the temperature difference between the film and the fluid also decreases faster for lower speeds as seen in Fig. 5.

It was verified that the sensitivity of the flow sensor depends on the laser current. The resonance wavelength shifts for a flow speed of 2.0 m/s are 0.18 and 0.37 pm for laser currents of 500 and 1000 mA, respectively. These results are also expected from application of Newton's law of cooling. In stationary conditions, assuming a similar dependence of the convection heat transfer coefficient on velocity, a lower amount of energy to be dissipated requires a smaller decrease in the temperature difference.

In view of the system sensitivity to flow variations, the configuration shown in Fig. 1 was also tested for flow speed measurement resolution. To do that, the velocity of the air flow into the chamber was changed gradually, and the wavelength variation was registered accordingly. Figure 6 shows the real time readout of the system, from which it was possible to estimate the resolution. The minimum flow velocity resolved by the system is 0.08 m/s (for a laser diode injection current of 1000 mA).

As previously seen, a possibility for increasing the sensitivity of the flowmeter is to increase the amount of laser power that is coupled into the cladding by the LPG. The improvements obtained by directly increasing the laser emission power, however, are limited by the device maximum output.

An alternative to increasing the laser power reaching the silver film is to change the order of the LPG cladding mode. In previous results we used a period of 385 μm, which corresponds to the higher cladding order mode we can access with the electric-arc technique. To study the effect of the cladding order mode, we use one more internal. This limitation can be overcome by using the UV writing process.

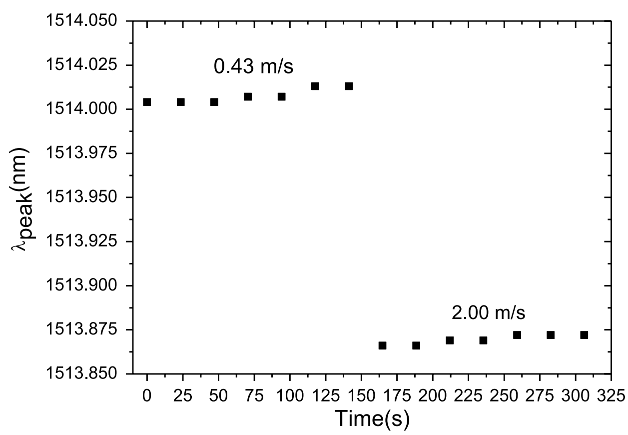


Fig. 6. Dynamic response of the sensor to a step change in flow speed.

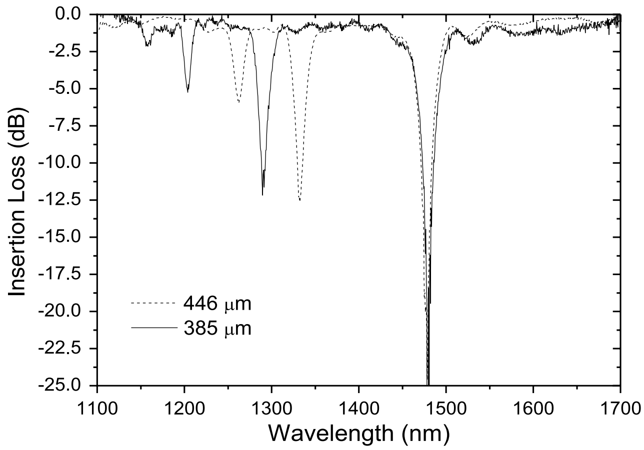


Fig. 7. LPG transmission spectra for modulation periods of $\Lambda = 385\,\mu$m and $\Lambda = 446\,\mu$m.

To have access to different cladding modes, gratings with periods of 446 and 385 μm were fabricated, corresponding to the third and fifth cladding modes, respectively.

The selection of these two particular modulation periods for the LPGs was made in order for the resonance wavelengths to coincide with the laser emission wavelength. Therefore, particular care was taken in the production of the LPGs, ensuring that they would have the same spectral characteristics, that is, similar spectral position of the resonance peaks and also similar associated losses. The results presented in Figs. 7 and 8 show that the two LPGs fabricated had very similar characteristics, also displaying a good overlap with the pump laser emission spectrum.

Each LPG was combined with an FBG having a silver layer overcoat. The two resulting sensor elements were tested for a pump laser current of 1000 mA. Figure 9 shows the evolution of the FBG resonance wavelength when the laser is turned on for LPGs with different periods. The results show

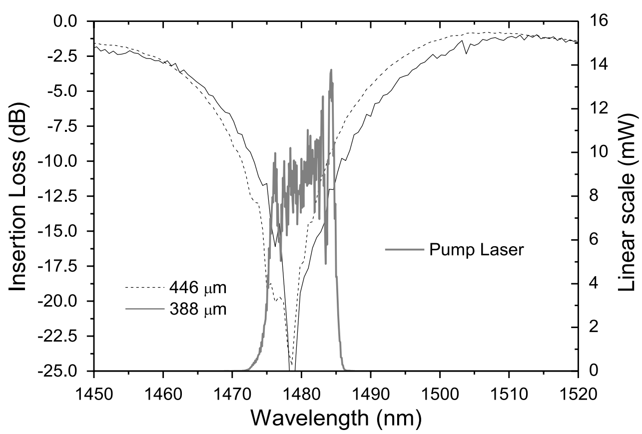


Fig. 8. Spectra of the pump laser emission and the LPG resonance at 1480 nm for the gratings with modulation periods of 385 and 446 μm.

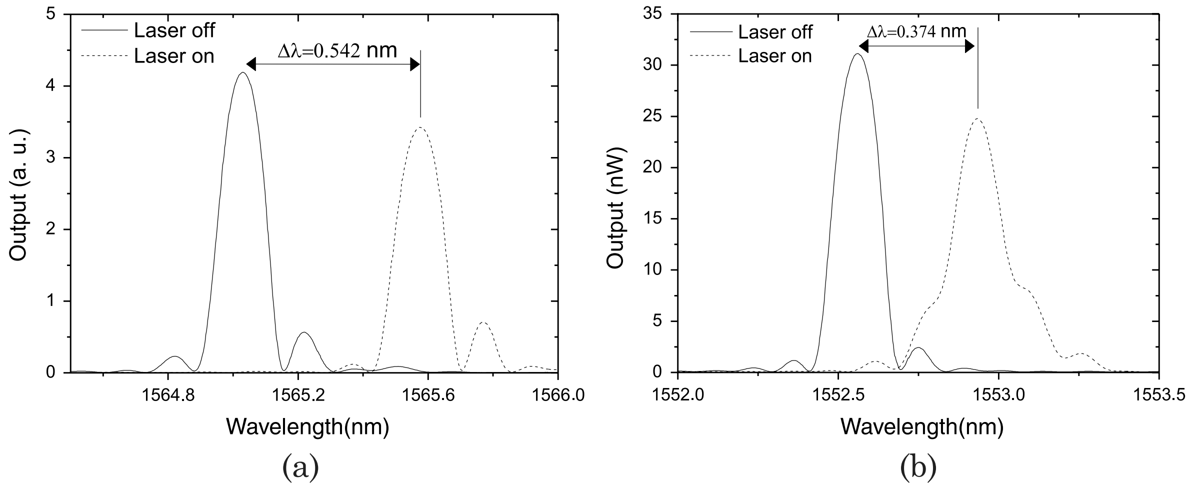


Fig. 9. Resonance wavelength shift of the FBG when the pump laser is turned on for LPG period of (a) $\Lambda = 385\,\mu$m and (b) $\Lambda = 446\,\mu$m.

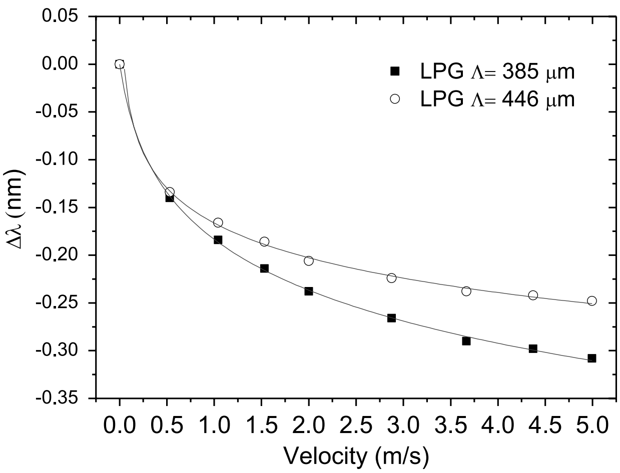


Fig. 10. Bragg grating response when it was heated by pump laser with 1000 mA for LPG $\Lambda = 385\,\mu$m and LPG $\Lambda = 446\,\mu$m.

that a greater spectral shift is obtained in the case of the LPG with a period of $385\,\mu$m. In this case a spectral shift is obtained that is 1.45 times greater than the one obtained with the sensing head using the LPG with a period of $446\,\mu$m. This is in agreement with the fact that the grating having the higher order mode couples power more effectively to the silver film in the fiber surface, resulting in a larger increase in temperature and a larger spectral shift.

The two sensors were tested as flowmeters. Figure 10 shows the spectral dependence of the FBG resonance wavelength as a function of the air velocity in the chamber for each LPG with different periods. The resonance wavelength shifts at a flow speed of $2.0\,\mathrm{m/s}$ are 0.21 and 0.24 nm for LPG periods of 446 and $385\,\mu$m, respectively. These results indicate that higher order cladding modes produce more effective energy transfer to the silver overcoat, yielding improved sensitivity.

4. Conclusions

In this work we demonstrated the possibility of heating a silver coated FBG structure with a high power laser diode when the cladding region is excited through an LPG with the same wavelength resonance as the laser emission. It was also shown that the proposed configuration enables the implementation of an all-optical hot-wire flowmeter that shares all the advantages of optical fiber sensors, indicating the feasibility of performing remote measurement of flow. In order to address the cross-sensitivity problems arising from measuring air flow at different temperatures, another FBG must be included—for instance, before the LPG—and a proper calibration of the sensor head as a function of the surrounding temperature should be performed. In the case of liquids, the LPG should be sealed inside a silica tube to prevent changes in the resonance wavelengths; at the same time, since the convection heat transfer coefficients are much larger, some insulation of the metal film may be required. The lossless nature of the proposed configuration also offers an intrinsic high multiplexing capability.

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