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High spatial resolution fibre -optic Fizeau interferometric strain sensor based on an in-fiber spherical microcavity

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High spatial resolution fibre -optic Fizeau interferometric strain sensor based on an in-fiber spherical microcavity

Abstract

We present a fiber-optic Fizeau interferometric strain sensor consisting of an in-fiber spherical microcavity of 39 μ m in diameter. The spherical microcavity was formed by splicing a normal single-mode fiber with a hollow-core photonic crystal fiber. We demonstrate that strain sensing can be realized by using the interference between the light signals reflected by the front and rear surfaces of the sphere. Experiments have shown that the strain sensor has a strain sensitivity of 3.36 μ m/ μ e and a temperature sensitivity of 1.35 μ m/ $^{\circ}$ C.

Keywords

strain, interferometric, fizeau, optic, fibre, resolution, spatial, high, spherical, microcavity, fiber, sensor

Disciplines

Engineering | Science and Technology Studies

Publication Details

Li, E., Peng, G. & Ding, X. (2008). High spatial resolution fibre -optic Fizeau interferometric strain sensor based on an in-fiber spherical microcavity. *Applied Physics Letters*, 92 (10), 101117-1-101117-3.

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Citation: [Applied Physics Letters](#) **92**, 101117 (2008); doi: 10.1063/1.2895637

View online: <http://dx.doi.org/10.1063/1.2895637>

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High spatial resolution fiber-optic Fizeau interferometric strain sensor based on an in-fiber spherical microcavity

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(Received 27 December 2007; accepted 18 February 2008; published online 13 March 2008)

We present a fiber-optic Fizeau interferometric strain sensor consisting of an in-fiber spherical microcavity of 39 μm in diameter. The spherical microcavity was formed by splicing a normal single-mode fiber with a hollow-core photonic crystal fiber. We demonstrate that strain sensing can be realized by using the interference between the light signals reflected by the front and rear surfaces of the sphere. Experiments have shown that the strain sensor has a strain sensitivity of 3.36 $\text{pm}/\mu\epsilon$ and a temperature sensitivity of 1.35 $\text{pm}/^\circ\text{C}$. © 2008 American Institute of Physics.

[DOI: 10.1063/1.2895637]

Fiber-optic strain sensing can be accomplished by employing different methods, including fiber Bragg gratings (FBGs), intrinsic or extrinsic fiber Fabry-Pérot (FP) interferometers, and single-mode-multimode-single-mode (SMS) structures.¹⁻⁶ FBG strain sensors have the so-called wavelength encoding and wavelength multiplexing features, hence they can be used for multipoint strain mapping. One issue with FBG strain sensors is their strain-temperature cross sensitivity, that is, both temperature and strain can contribute to the Bragg wavelength shifts. A FBG fabricated with a standard communication fiber has a temperature sensitivity of 11 $\text{pm}/^\circ\text{C}$ and a strain sensitivity of 1.22 $\text{pm}/\mu\epsilon$ in the 1550 nm band, which means that a FBG is much more sensitive to temperature than to strain. Therefore, a certain kind of temperature compensation or temperature-strain discrimination technique has to be adopted in FBG strain sensing. Extrinsic fiber FP strain sensors fabricated by using fiber end faces as reflection mirrors and with air gaps as the FP cavities can be temperature insensitive when the sensors are properly designed. SMS strain sensors, in which multimode interferences are utilized, have an extremely simple structure and a very low fabrication cost. The SMS sensors have a temperature sensitivity identical to that of FBG sensors and a strain sensitivity which is almost twice of that of FBG strain sensors in value but with an opposite polarity.

In this letter, we present a high special resolution fiber-optic Fizeau interferometric strain sensor (FISS) with an in-fiber spherical microcavity. The spherical microcavity was formed by splicing a normal single-mode fiber (SMF) with a hollow-core photonic crystal fiber (HC-PCF). We demonstrate that strain sensing can be realized by using the interference between the light signals reflected by the front and rear surfaces of the sphere.

Fiber splicing between SMFs and PCFs is necessary in various PCF applications.⁷ It is noted that by varying splicing conditions, splices with different structures can be obtained. With a SMF and a HC-PCF, under certain splicing settings, a microsphere can be formed at the end of the SMF core. Figure 1(a) shows a microscopic image of a spherical

microcavity produced when splicing a standard communication fiber (Corning SMF-28) to a hollow-core photonic band gap fiber (HC-1550-02 from Blazephotonics) with a selected splicing program from a fusion splicer (Fitel S175). We found that with a prefuse time of 290 ms, an arc-duration of 3000 ms, and a Z-push distance of 17 μm , spherical microcavities could be formed with reasonable reproducibility if the HC-PCF was properly cleaved. The diameter of the microsphere shown in Fig. 1(a) was measured as 39 μm . A scanning electron microscopy (SEM) image of the HC-PCF cross section is shown in Fig. 1(c).

As shown in Fig. 1(b), light transmitting in the core of the SMF will be partially reflected by the silica-air interface (front surface of the cavity) when the light reaching at the

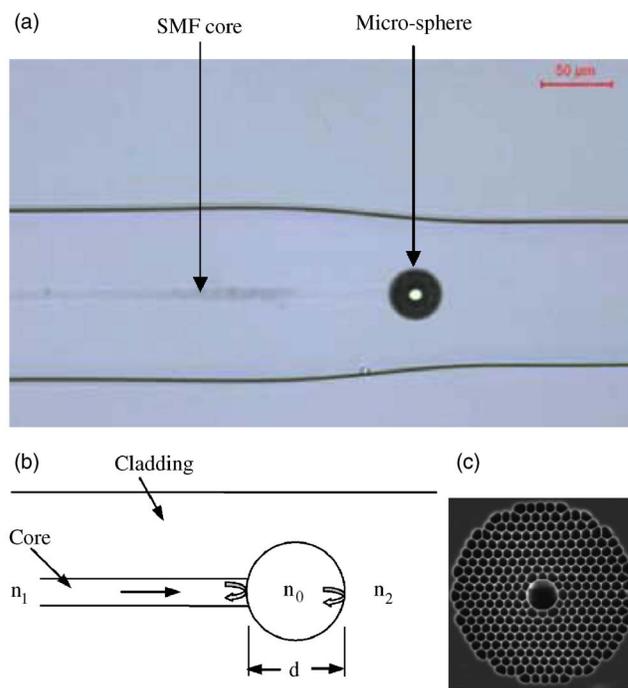


FIG. 1. (Color online) (a) Microscopic image of a spherical microcavity produced when splicing a standard communications fiber to a hollow core photonic band gap fiber, (b) Schematic diagram of the microcavity. (c) SEM image of the hollow-core photonic band gap fiber.

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microsphere. The transmitted light will be reflected by the air-silica surface (rear surface) back to the fiber core and interfere with the light reflected by the front surface. The light beam exiting from a right-angle cleaved SMF can be modeled as a Gaussian beam,⁸ with a beam waist locating at the fiber end surface and a waist diameter being equal to the mode field diameter of the SMF. Therefore, the interference process can be treated by using a Gaussian beam model and the ABCD law (The ABCD law is widely used in Gaussian optics, and A, B, C, and D are four parameters).^{9,10} Since the reflectivity at the silica/air interfaces is low (less than 4%), multiple reflections can be neglected, leading to a Fizeau interference model to be considered.

The interferogram produced by the microsphere is determined by the phase delay between the light signals reflected respectively by the front and rear surfaces. Suppose that the waist radius of the beam exiting from the front surface is w_0 and the wavelength is λ . As the sphere diameter d is comparable to the Gaussian beam Rayleigh range, $z_0 = \pi w_0^2 / \lambda$, in our case, we need to consider the contribution from the Guoy phase shift, which can be expressed as $\tan^{-1}(z/z_0)$, with z as the propagation distance from the beam waist.⁹ When the beam reaches the rear surface, a phase delay of $\phi_1 = 2\pi n_0 d / \lambda - \tan^{-1}(d/z_0)$ will be produced, where n_0 is the refractive index of air. The concave rear surface acts like a plane mirror with a reflection coefficient of r and a lens with a focal length of $d/4$. After reflection by the concave rear surface, the beam is transformed to a new Gaussian beam. By using the Gaussian beam transformation theory,¹¹ one can obtain the waist radius $w_{01} = w_0 d (9d^2 + 16z_0^2)^{-1/2}$. The beam waist locates on the optical axis, and the distance between the transformed beam waist and reflection surface is $l = d(3d^2 + 4z_0^2) / (9d^2 + 16z_0^2)$. Propagating from the rear surface back to the front surface, the reflected light experiences a phase delay $\phi_2 = 2\pi n_0 d / \lambda - \tan^{-1}(l/z_{01}) - \tan^{-1}[(d-l)/z_{01}]$, with $z_{01} = \pi w_{01}^2 / \lambda$. Therefore, we can calculate the total phase delay $\phi = \phi_1 + \phi_2 = 4\pi n_0 d / \lambda - \tan^{-1}(l/z_{01}) - \tan^{-1}[(d-l)/z_{01}]$.

The condition for a constructive interference is $\phi = 2N\pi$ (N is a positive integer), from which one can readily obtain the resonance wavelength, $\lambda_N = 4\pi n_0 d / (2N\pi + \tan^{-1}(d/z_0) + \tan^{-1}(l/z_{01}) + \tan^{-1}[(d-l)/z_{01}])$, and the wavelength spacing between two adjacent interference maxima (or minima), $\Delta\lambda = \lambda^2 / (2n_0 d)$.

It is obvious that the resonance wavelength is not only a function of the sphere diameter but is also related to the Guoy phase shifts which should be considered only in the near field of a Gaussian beam.

A measured interferogram is shown in Fig. 2. Limited by the spectral range (1530–1560 nm) of the light source available in the experiments, only one minimum and one maximum were detected, and the spacing between them were measured as 15.5 nm, indicating $\Delta\lambda = 31.0$ nm. Using the measured value of d and taking $n_0 = 1$ and $\lambda = 1550$ nm, we calculated $\Delta\lambda$ as 30.8 nm, which agrees well with the measured wavelength spacing.

When an axial strain is applied to the fiber segment containing the microsphere, the cavity length will be changed; hence, the wavelength corresponding to the interference maximum or minimum will vary. Therefore, by measuring the wavelength shift, one can determine the variation of d or

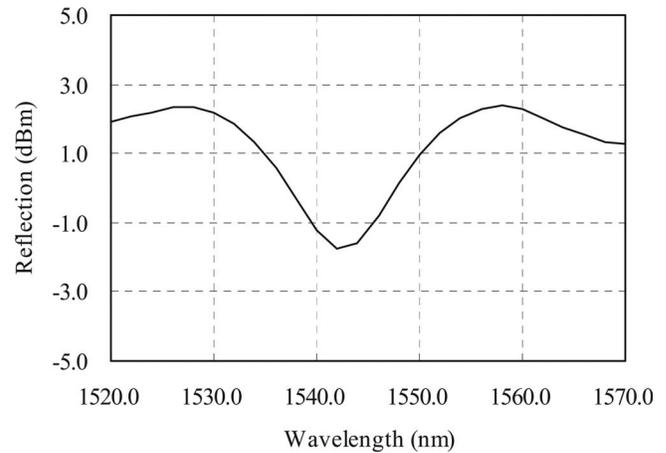


FIG. 2. Measured reflection spectrum of the microcavity Fizeau interferometer.

the strain experienced by the fiber segment containing the microsphere.

To experimentally demonstrate the sensing ability of the in-fiber spherical microcavity, an experimental setup, as shown in Fig. 3, was constructed. A FBG fabricated by using a photosensitive fiber with a cladding diameter of 125 μm was connected to the microcavity FISS as a strain indicator (the strain sensitivity of the FBG is known to be 1.22 pm/ μe). The cascaded strain sensors were supported by two fiber holders, one of them was mounted directly to an optical table and another was mounted to a translation stage. The light source used in our experiments was an amplified spontaneous emission (ASE) broadband source with an output power of 5 mW and a central wavelength of 1550 nm and a bandwidth of about 35 nm. An optical circulator was employed to separate the input light and the reflected light and to redirect the reflected light to an optical spectrum analyzer for recording the spectra and measuring the wavelength shifts. Shown in Fig. 4 is a reflection spectrum produced by the FISS and the FBG, where the sharp peak is the FBG reflection. By adjusting the translation stage, we could vary the tensile stress applied to the sensors. From the recorded spectra, one could measure the wavelength shifts produced by the FBG and the FISS. As the interfering troughs or peaks produced by the FISS are relatively broad, the curve fitting and peak (or bottom) searching functions provided with the OSA were used for accurately determining the wavelength shifts. Plotted in Fig. 5 are the measured wavelength shifts produced by the microcavity FISS against the FBG wavelength shifts. It can be seen that the peak wavelength moves linearly to a longer wavelength with an increase of strain. The solid line in Fig. 5 is a linear curve fit to the measured data and has a slope of 2.757. Taking the FBG strain sensitivity (1.22 pm/ μe) into account, we calculated the strain sen-

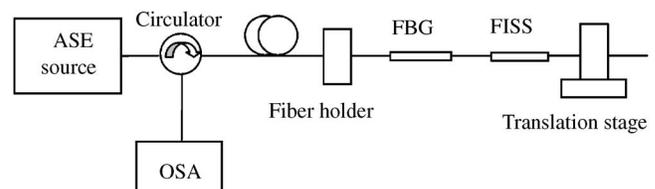


FIG. 3. Experimental setup for strain measurements.

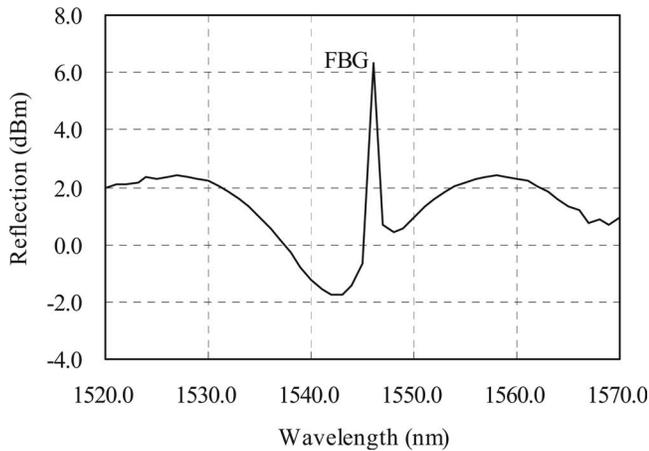


FIG. 4. Reflection spectrum produced by a microcavity Fizeau interferometer and a fiber Bragg grating.

sitivity of FISS as $3.36 \text{ pm}/\mu\epsilon$, which is a significant improvement over FBG strain sensors.

We also measured the temperature sensitivity of the FISS by positioning the sensor in an environmental chamber (Espec SH641) for changing the temperature. As shown in the inset of Fig. 5, the wavelength increases with the increase of temperature, and an average temperature sensitivity of $1.35 \text{ pm}/^\circ\text{C}$ can be identified.

In conclusion, we have demonstrated that the spherical microcavity formed by splicing a normal single-mode fiber

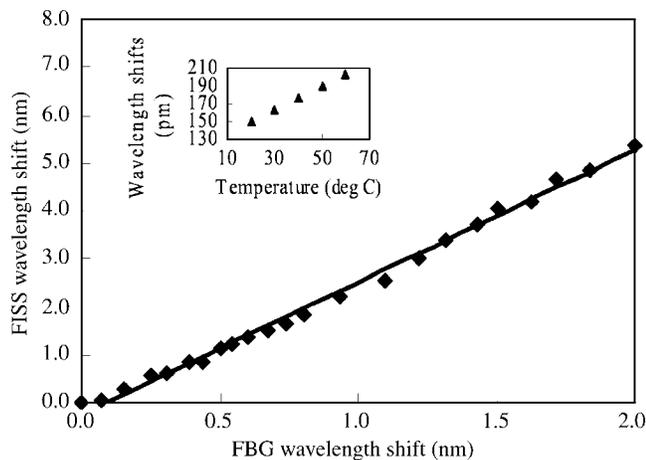


FIG. 5. Wavelength shifts produced by the Fizeau interferometric strain sensor against the FBG wavelength shifts under different tensions. The inset shows the measured wavelength shifts at different temperatures.

with a hollow-core photonic crystal fiber can be used as a strain sensor. The gauge length of the strain sensor is determined by the length of the microcavity, which makes a high spatial resolution strain sensing possible. Experimental results have shown that a strain sensitivity of $3.36 \text{ pm}/\mu\epsilon$ can be achieved. This strain sensitivity is much higher than that of the most popularly used FBG strain sensors. The microcavity strain sensor is temperature insensitive (with a temperature sensitivity of $1.35 \text{ pm}/^\circ\text{C}$), which means that temperature compensation may not be necessary for most of the strain sensing applications. Other advantages of the proposed strain sensor include an extremely simple structure and low cost to fabricate.

It should be pointed out that the presence of a microcavity inside a fiber could reduce the tensile strength of the fiber sensor, which would set a limit to the maximum strain the sensor can be used for. In our experiments, the fabricated sensors were tested for strains larger than $3000\mu\epsilon$ without breaking the sensors.

Since the reflections at the air-silica interfaces which form the Fizeau interferometer are low, the interferogram is normally weak. However, this will not affect the measurement accuracy as long as an interfering peak or trough can be identified because the wavelength is used as an indicator to the measured strain.

This work was supported, in part, by Natural Science Foundation of China (Grant No. 60578054), Tianjin Municipal Commission of Education, Tianjin Municipal Science and Technology Commission, and Tianjin University through the “111 Project” (B07014).

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