Quantum Electronics **41** (9) 821 – 823 (2011)

PACS numbers: 07.60.Ly; 07.60.Vg; 42.81.Pa
DOI: 10.1070/QE2011v041n09ABEH014677

Effect of small variations in the refractive index of the ambient medium on the spectrum of a bent fibre-optic Fabry – Perot interferometer

Yu.N. Kulchin, O.B. Vitrik, S.O. Gurbatov

Abstract. **The phase of light propagating through a bent optical fibre is shown to depend on the refractive index of the medium surrounding the fibre cladding when there is resonance coupling between the guided core mode and cladding modes. This shifts the spectral maxima in the bent fibre-optic Fabry – Perot interferometer. The highest phase and spectral sensitivities achieved with this interferometer configuration are 0.71 and 0.077, respectively, and enable changes in the refractive index of the ambient medium down to 5×10^{-6} to be detected. This makes the proposed approach potentially attractive for producing highly stable, precision refractive index sensors capable of solving a wide range of liquid refractometry problems.**

Keywords: *single-mode optical fibre, fibre Fabry – Perot interferometer, precision refractometry of liquids, resonance coupling of guided modes.*

Traditional optical refractometers, e.g. Abbe, Pulfrich and Rayleigh refractometers, with sensitivities from 10^{-3} to 10^{-4}, are widely used to measure the refractive index of liquids and the concentration of substances in solutions for the identification, quantitative analysis and structural characterisation of chemical compounds; quality control in the production of petroleum derivatives; purity analysis of pharmaceuticals; environmental monitoring; physicochemical characterisation of substances; and monitoring of biochemical reactions [1, 2]. At the same time, advances in biochemistry and medicine and ever more stringent requirements for environmental monitoring pose problems that require that the sensitivity of refractometers be improved to 10^{-6} – 10^{-7}. In view of this, a novel class of devices has been developed for refractive index measurements, which take advantage of surface plasmon resonance [3]. Such measuring devices have found wide application [3]. Unfortunately, most of them are rather unwieldy and difficult to use, especially when high-speed analyses under field conditions or remote measurements are needed [1 – 3].

It is known that a transition from bulk optical components to optical fibres makes it possible to simplify the assembly, installation and use of optical measuring devices and to reduce their dimensions and weight and offers the possibility of remote measurements, in particular in real time [4]. Currently, a large number of fibre-optic refractometer configurations are known, e.g. those based on fibre Bragg gratings, long-period fibre gratings, and fibre-optic Mach – Zehnder, Michelson or other interferometers and those employing a core diameter mismatch and tapered fibres [5 – 9]. Despite the significant advances in this area of research, further work is needed to achieve high sensitivity of refractometers in combination with high reliability and a potentially low cost, which usually can be ensured by simplifying the design of such devices [4, 6 – 8].

An interesting approach to the problem of creating fibre-optic refractometers was proposed by Wang et al. [10]. They determined the refractive index of a liquid surrounding an optical fibre by measuring the power loss of guided optical radiation in a single-mode fibre while ensuring resonance coupling between the fundamental mode of the fibre core and cladding modes. Such coupling can be achieved without disturbing the total internal reflection conditions for the fundamental core mode owing to the tunnelling effect that arises when light waves are incident on the core – cladding interface of a bent optical fibre. The mode coupling efficiency then depends on the relationship between the refractive indices of the cladding and ambient medium, which ensures a sensitivity to refractive index changes of $\sim10^{-4}$ [9].

This configuration ensures high stability and an extremely simple design of the sensor (basically, the refractometer consists of one fibre turn of appropriate radius), but its sensitivity proves insufficient for solving current liquid refractometry problems. We believe that it can be improved by measuring not amplitude changes but phase changes of the fundamental mode of the fibre. Such changes can be evaluated from the shift of spectral maxima of a fibre Fabry – Perot interferometer. The modulation of the spectrum of a bent fibre-optic Fabry – Perot interferometer in response to small variations in the refractive index of the ambient medium is, however, poorly studied, which has led us to address this issue.

The Fabry – Perot interferometer studied has the form of a bent step-index single-mode silica fibre (Fig. 1) with metallic mirror coatings on its end faces. The interferometer is immersed in a liquid with a refractive index n_3, which exceeds the refractive index of the fibre cladding, n_2. Fibre bending causes some of the guided light to tunnel into the fibre cladding, exciting an appropriate set of eigenmodes in the cladding. The complex Fresnel reflection coefficient of the cladding modes at the cladding/liquid interface and, hence, their amplitude and phase depend on the relationship between n_2 and n_3. The selection of a certain fibre bending radius ensures resonance coupling between the cladding modes and fundamental core mode. As a consequence, the phase of the core

Yu.N. Kulchin, O.B. Vitrik, S.O. Gurbatov Institute for Automation and Control Processes, Far Eastern Branch, Russian Academy of Sciences, ul. Radio 5, 690041 Vladivostok, Russia;
e-mail: director@iacp.dvo.ru, oleg_vitrik@mail.ru, gurbatov_slava@mail.ru

Received 20 June 2011; revision received 25 July 2011
Kvantovaya Elektronika **41** (9) 821 – 823 (2011)
Translated by O.M. Tsarev

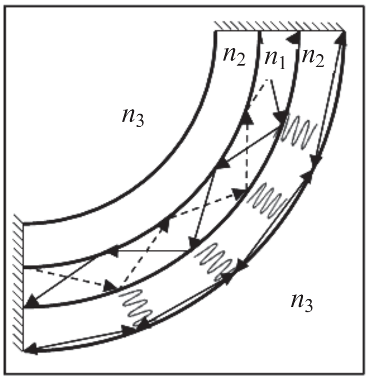

Figure 1. Light propagation in a bent fibre-optic Fabry–Perot interferometer; n_1, n_2 and n_3 are the refractive indices of the core, cladding and liquid.

mode also depends on n_3, leading in turn to a shift of resonances in the spectrum of the Fabry–Perot interferometer.

To find the bending radii that ensure resonance coupling of the core and cladding modes in a single-mode fibre, we used a theoretical model proposed previously [11]. In this model, the power attenuation coefficient, α, of the fundamental guided mode is related to the bending radius, R, of a single-mode fibre by

$$\alpha(R) = \frac{\kappa^2 \exp(-2\gamma^3 R/3k^2 n_2^2)}{\gamma\beta V^2 K_1^2(\rho\gamma)}$$

$$\times \int_0^\infty \frac{\sqrt{\chi_2(R,\zeta)\chi_3(R,\zeta)}\exp(-\gamma R\zeta^2/k^2 n_2^2)}{\chi_2(R,\zeta)\cos^2\Theta(\zeta) + \chi_3(R,\zeta)\sin^2\Theta(R,\zeta)}\mathrm{d}\zeta, \qquad (1)$$

where ρ is the core radius; $k = 2\pi/\lambda$ is the wavenumber; λ is the wavelength; $V = k\rho\sqrt{n_1^2 - n_2^2}$ is the reduced frequency; n_1 is the refractive index of the fibre core; β is the propagation constant of the fundamental mode; $\kappa = \sqrt{n_1^2 k^2 - \beta^2}$; $\gamma = \sqrt{\beta^2 - n_2^2 k^2}$; K_1 is the first-order Macdonald function; b is the outer radius of the cladding; ζ is the spatial frequency;

$$\chi_q(R,\zeta) = (2k^2 n_q^2/R)^{2/3}[-X_q(R,\zeta)];$$

$$X_q(R,\zeta) = [R/(2k^2 n_q^2)]^{2/3}[\beta^2 + \zeta^2 - k^2 n_q^2 1 + 2b/R];\ q = 2,3;$$

$$\Theta(R,\zeta) = \tfrac{2}{3}[-X_2(R,\zeta)]^{3/2} + \pi/4.$$

Figure 2 presents $\alpha(R)$ calculated by Eqn (1) (solid line) and the present experimental data (filled squares) for a single-mode fibre with $\rho = 4.15$ μm, $n_1 = 1.467$, $n_2 = 1.462$ and $n_3 = 1.479$ at a guided wavelength $\lambda = 1.55$ μm. As seen, $\alpha(R)$ has several maxima, which are due to the resonance coupling between the core mode and cladding modes [11].

Based on the data in Fig. 2, we fabricated fibre Fabry–Perot interferometers with bending radii $R = 9.4$ and 10.7 mm. The bending radius 8.3 mm, which also ensures resonance coupling between the core and cladding modes according to Fig. 2, was not used because it carried the risk of mechanical failure of the fibre. In addition, we fabricated fibre Fabry–Perot interferometers with bending radii of 10.1 mm and 5 m, which cause no resonance coupling (Fig. 2).

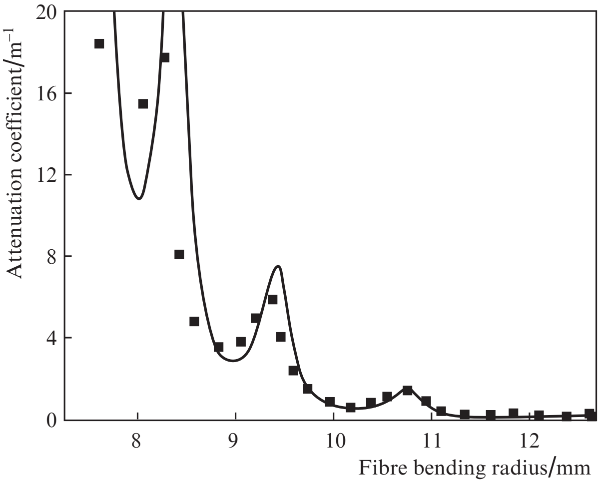

Figure 2. Guided power attenuation coefficient as a function of bending radius for a single-mode optical fibre. The solid line was obtained by calculation using Eqn (1) and the filled squares represent experimental data.

Mirror coatings (gold–palladium alloy) on the fibre end faces were produced by ion sputtering. The thickness of the coatings was selected so as to achieve high finesse of the cavity, which can be ensured by increasing the reflectance of the mirrors and, accordingly, the thickness of the reflective coatings. At the same time, too great a thickness of the input coating, which serves to couple the beam into the interferometer cavity, may lead to an increase in optical power losses and, hence, limit the sensitivity of the interferometer to changes in n_3. In view of this, the thickness of the input mirror was $h = 40$ nm, which ensured a reflectance $r^2 \sim 50\%$. The output mirror had $h = 60$ nm and $r^2 \sim 98\%$.

Figure 3 schematically shows the experimental configuration used to measure the shift of spectral maxima of a bent Fabry–Perot interferometer in response to changes in the refractive index of the ambient medium. The radiation from a stabilised superluminescent diode with a centre wavelength of 1550 nm (*1*) was coupled into a bent fibre-optic Fabry–Perot cavity (*3*), which was firmly secured to a substrate (*4*) and immersed in a liquid (*5*). Figure 4 plots the measured shift of the spectral maxima, $\Delta\lambda$, of the interferometer against the refractive index of the liquid, n_3. As seen, resonance coupling between the core mode and cladding modes of the interferometer leads to significant shifts of the maxima [curves (*1*, *2*)]. When there is no resonance coupling, n_3 has little effect on the spectrum of the light propagating through the core of the fibre-optic interferometer [curves (*3*, *4*)]. The $\Delta\lambda(n_3)$ curves obtained in the case of resonance coupling between the core and cladding modes in the fibre Fabry–Perot interferometer have the steepest slope in the range where the refractive index of the liquid, n_3, is closest to that of the fibre cladding, n_2. The slope of curve (*1*) is $\gamma = \mathrm{d}\lambda/(\lambda \mathrm{d}n_3) = 0.077$. The corresponding phase sensitivity of the fundamental mode per unit length, l, of the fibre is $\xi = \lambda \mathrm{d}\varphi/(l\mathrm{d}n_3) = 0.71$. Such values allow one to detect changes in the refractive index of the ambient medium down to 5×10^{-6}. The sensitivity can be further improved by increasing the length of the interferometer, e.g. by using multiturn configurations. It follows from the data in Fig. 4 that both γ and ξ gradually decrease with increasing n_3 and become approximately one order of magnitude smaller at $n_3 = 1.479$. It seems likely that this is due to the reduction in the mutual

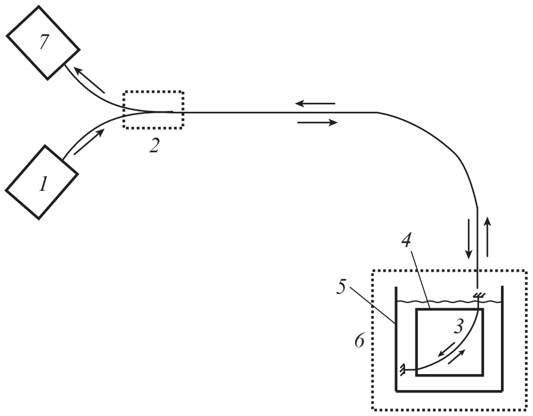

Figure 3. Schematic of the experimental configuration: (*1*) stabilised superluminescent diode with a centre wavelength of 1550 nm, (*2*) Y-type fibre coupler, (3) bent fibre-optic Fabry–Perot interferometer, (*4*) substrate, (*5*) cell containing a liquid whose refractive index is to be determined, (*6*) thermostat, (*7*) optical spectrum analyser.

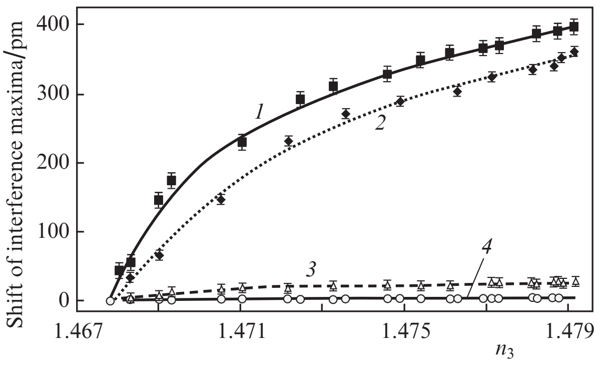

Figure 4. Shift of the interference maxima in a fibre Fabry–Perot interferometer against the refractive index of the ambient medium, n_3, at a fibre bending radius R = (*1*) 9.4 mm, (*2*) 10.7 mm, (*3*) 10.1 mm and (*4*) 5 m.

influence of the core and cladding modes with increasing cladding–liquid index difference. This assumption is supported by the fact that n_3 has a similar effect on the amplitude of the fundamental mode of the single-mode fibre. Indeed, it directly follows from (1) that, in the case of resonance coupling between the fundamental mode and cladding modes, the curves have the steepest slope at $n_3 \approx n_2$ and the slope decreases with increasing n_3.

Thus, the present results demonstrate that the phase of light propagating through a bent optical fibre depends on the refractive index of the ambient medium when there is resonance coupling between the guided core mode and cladding modes. This shifts the spectral maxima in the bent fibre-optic Fabry–Perot interferometer. The highest phase and spectral sensitivities achieved with the bent Fabry–Perot interferometer are 0.71 and 0.077, respectively. These parameters allow one to detect changes in the refractive index of the ambient medium down to 5×10^{-6}. This makes the proposed approach potentially attractive for producing highly stable, precision refractive index sensors capable of solving a wide range of liquid refractometry problems.

References

1. Born M., Wolf E. *Principles of Optics* (Oxford: Pergamon, 1969; Moscow: Nauka, 1973).
2. Ioffe B.V. *Refraktometricheskie metody khimii* (Refractometric Methods in Chemistry) (Leningrad: Khimiya, 1974).
3. Homola J., Yee S.S. *Sens. Actuators B*, **54**, 3 (1999).
4. Kuzyk M.G. *Polymer Fiber Optics: Materials, Physics, and Applications* (Boca Raton: CRC Press, 2006).
5. Liang W., Huang Y.Y., Xu Y., Lee R.K., Yariv A. *Appl. Phys. Lett.*, **86**, 151122 (2005).
6. Villatoro J., Monzón-Hernández D. *J. Lightwave Technol.*, **24**, 1409 (2006).
7. Lu P., Men L., Sooley K., Chen Q. *Appl. Phys. Lett.*, **94**, 131110 (2009).
8. Wei T., Han Y., Li Y., Tsai H.-L., Xiao H. *Opt. Express*, **16**, 5764 (2008).
9. Vasil'ev S.A., Dianov E.M., Kurkov A.S., Medvedkov O.I., Protopopov V.N. *Kvantovaya Elektron.*, **24**, 151 (1997) [*Quantum Electron.*, **27**, 146 (1997)].
10. Wang P., Semenova Yu., Wu Q., Farrell G., Ti Yu., Zheng J. *Appl. Opt.*, **48**, 31 (2009).
11. Faustini L., Martini G. *J. Lightwave Technol.*, **15**, 671 (1997).