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A refractometer based on fiber-to-liquid planar waveguide coupler

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Abstract

A fiber-optic liquid refractometer based on fiber-to-planar waveguide coupler is proposed and demonstrated. The liquid plays a role of highly multimode planar waveguide (PWG), which is evanescently coupled to a side-polished single mode fiber. A simple method, which acquire the refractive index (RI) of a liquid using two adjacent resonance wavelengths of the coupler, is presented. Furthermore, it is experimentally shown that the measurement range of RI can be expanded by series connection of two different fiber-to-PWG couplers. The resolution of the proposed and fabricated refractometer is of the order of 10^{-5} to 10^{-4}.

Keywords: Refractometer; Side-polished fiber; Directional coupling; Planar waveguide; Coupler

1. Introduction

In-line fiber-optic sensors offer many attractive benefits such as small size, light weight, high resolution and high immunity to electromagnetic wave as well as easiness in multiplexing and distributed sensing. In particular, side-polished single mode fibers, whose transmission characteristics are strongly related to the optical characteristics of the external medium placed on their polished cladding surfaces, have been widely used to implement optical sensors. Furthermore, their wavelength selectivity are very strongly related to a high index multimode planar waveguide (PWG) on the side-polished cladding surface. Such structures defined as the fiber-to-PWG couplers have been investigated as fiber-optic sensors for detecting the various physical parameters such as temperature [1,2], humidity [3], displacement [4] and optical constant of metal films [5]. In addition, the couplers have been studied as liquid refractometers with high sensitivity and high resolution [6–8]. In general, the liquid acts as a superstrate (upper cladding) of the PWG, and the sensitivity of resonance position in wavelength to the refractive index (RI) of superstrate is used to obtain the RI of liquid. However, the couplers do not show sharp resonance spectra when the RIs of liquids exceed that of the fiber core [9]. Therefore, they cannot operate as a refractometer for high index liquids.

In this paper, we propose and demonstrate a refractometer based on fiber-to-PWG coupler for liquids whose RIs are greater than that of the fiber core. The high index liquid, which looks like a thin liquid slab on the side-polished block, acts as a multimode PWG. A simple method to acquire the RIs of the liquids using the two resonance wavelengths is presented. The characteristics of the proposed fiber-to-liquid PWG coupler and the conventional fiber-to-PWG coupler where the liquid acts as upper cladding of the PWG, are evaluated in terms of performances of refractometers. Experiments show that a wide range of RI can be measured using the total wavelength response of series connected two different fiber-to-PWG couplers.

2. Structure and measurement principle

The schematics of the proposed refractometer for high index liquid is shown in Fig. 1(a). Two spacers made of microscope cover glass are placed between the surface of fiber block and the superstrate. Fig. 1(b) shows the cross-sectional view of the device. If the thin slab-like volume, which is defined by the bottom of superstrate and sides of the two spacers and top of the side-polished fiber block, infused with a high RI liquid, the device operates as a fiber-to-liquid PWG coupler. Thicknesses

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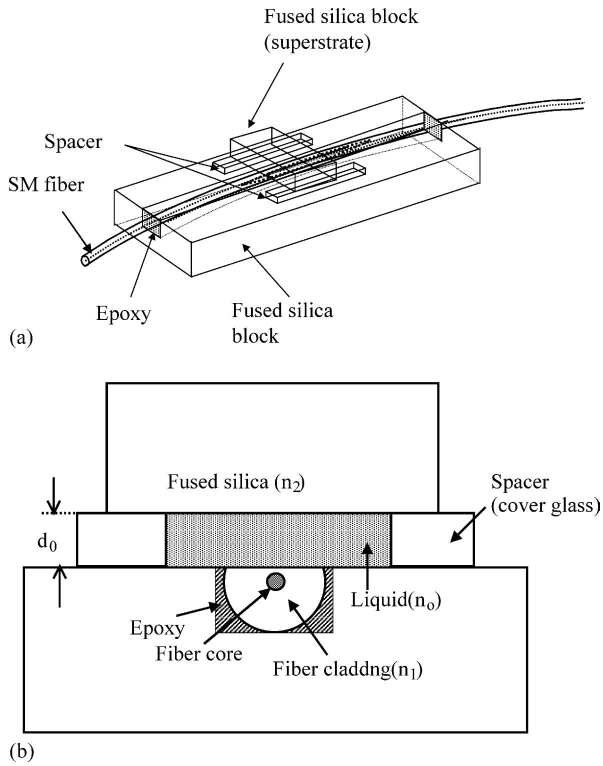

Fig. 1. Structure of proposed refractometer (a) schematic view and (b) longitudinal cross-sectional view.

of the spacers (d_0) should be high enough for the infused liquid to become a highly multimode PWG. The RI of each component is indicated in Fig. 1(b).

In general, a fiber-to-PWG coupler can be described as an asymmetric directional coupler. Optical resonant power coupling from the fiber to the multimode PWG occurs when the effective RI of the highest PWG mode is close to the effective RI (n_{ef}) of the fiber mode. Accordingly, the light components satisfying the phase matching condition can be removed from the fiber. The peak dip wavelengths (resonance wavelengths) can then be easily calculated using the eigenvalue equations of the PWG and fiber [10]. The eigenvalue equation for the mth order PWG mode can be expressed as follows:

$$\frac{2\pi}{\lambda} d_0 (n_0^2 - n_{em}^2)^{1/2} = m\pi + \phi_1 + \phi_2. \quad (1)$$

where λ is the input free space wavelength, n_0 and n_{em} denote the RI of guiding layer (liquid) of the PWG and the effective RI of the mth order PWG mode, respectively, and ϕ_1 and ϕ_2, given by the following equation, are the phase shifts of the guided mode at the lower and upper planar waveguide boundaries, respectively:

$$\phi_i\,(i = 1 \text{ or } 2) = \tan^{-1} \varsigma \frac{(n_{em}^2 - n_i^2)^{1/2}}{(n_0^2 - n_{em}^2)^{1/2}} \quad (2)$$

where n_1 and n_2 denote the RI for the lower and upper cladding layers of the PWG, respectively, as indicated in Fig. 1(b), and ς is the polarization-dependent constant (1 for TE and $(n_0/n_i)^2$ for TM).

Meanwhile, for the single mode fiber, the eigenvalue equation expressed in terms of Bessel functions [11] is as follows:

$$\frac{uJ_1(u)}{J_0(u)} = \frac{wK_1(w)}{K_0(w)}. \quad (3)$$

where u and w, given by the following equations, are the normalized transverse propagation constants in the core and cladding, respectively,

$$u = k_0 a\sqrt{n_{co}^2 - n_{ef}^2}, \qquad w = k_0 a\sqrt{n_{ef}^2 - n_{cl}^2}. \quad (4)$$

where n_{co} and n_{cl} are the refractive index of the fiber core and cladding, respectively, n_{ef} the effective refractive index of the SM fiber, and a and k_0 denote the radius of the fiber core and propagation constant in the free space, respectively. The resonance wavelength (λ_m) of the mth order mode can be computed by substituting the phase matching condition, i. e. $n_{em} = n_{ef}$, into Eqs. (1) and (2):

$$\lambda_m = \frac{2\pi d_0 (n_0^2 - n_{ef}^2)^{1/2}}{m\pi + \phi_1 + \phi_2}. \quad (5)$$

Here, we present a simple method to obtain RI of a liquid using two adjacent resonance wavelengths of the fiber-to-liquid PWG coupler. Let us define λ_{m+1} as resonance wavelength of $m+1$th mode order of PWG and $\Delta\lambda$ denotes $\lambda_m - \lambda_{m+1}$.

$$\frac{1}{\lambda_{m+1}} - \frac{1}{\lambda_m} = \frac{\Delta\lambda}{\lambda_{m+1}\lambda_m} = \frac{1}{2\pi d_0 (n_0^2 - n_{ef}^2)^{1/2}} \quad (6)$$

The expression for RI of liquid is

$$n_0 = \sqrt{\frac{(\lambda_{m+1}\lambda_m)^2}{(2\pi d_0\,\Delta\lambda)^2} + n_{ef}^2} \quad (7)$$

where $\Delta\lambda = \lambda_m - \lambda_{m+1}$. Mode orders, m and $m+1$, are not shown explicitly in Eq. (7), but their specific values are implicitly included in λ_m and λ_{m+1}. The mode order increases one by one as the resonance wavelength decreases. One can substitute λ_{m+k} for λ_{m+1}, and then should use $\Delta\lambda = \lambda_m - \lambda_{m+k}$ and the following equation for RI of liquid:

$$n_0 = \sqrt{\frac{(k\lambda_{m+k}\lambda_m)^2}{(2\pi d_0\,\Delta\lambda)^2} + n_{ef}^2} \quad (8)$$

where k is a positive integer. The greater the value of k, the better the resolution and the sensitivity are because the larger the value of k, the larger the value of $\Delta\lambda$ is for RI of given liquid. However, the larger k may decrease the accuracy of RI because of the chromatic dispersion between two resonance wavelengths. Eq. (8) is derived upon the assumption that RI is constant at two separate wavelengths.

3. Fabrication

We have prepared single-mode (SM) side-polished fiber blocks. A silica block (length: 25 mm; width: 10 mm; height: