# Microstructured optical fiber refractive index sensor

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Received October 9, 2009; revised January 27, 2010; accepted February 1, 2010; posted February 4, 2010 (Doc. ID 118349); published March 15, 2010

We describe a dual-core microstructured optical fiber designed for refractive index sensing of fluids. We show that by using the exponential dependence of intercore coupling on analyte refractive index, both large range and high sensitivity can be achieved in the one device. We also show that selective filling of the microstructure with analyte can increase the device sensitivity by approximately 1 order of magnitude. © 2010 Optical Society of America

*OCIS codes:* 060.4005, 060.2370, 120.3180.

A significant problem for increasing the sensitivity of evanescent-wave-based optical sensors is how to increase the overlap of the optical field with the analyte without incurring bend and scattering losses associated with weak guidance (e.g., owing to low NA or small core diameter). It has been proposed that using the analyte as a waveguide [1] in a microstructured host can increase the sensitivity of optical sensing systems by 1 order of magnitude; however, this incurs other problems, such as how to provide accurate coupling to a fluid waveguide and how commonly available cladding materials restrict the minimum refractive index of analyte that can act as a waveguide, a problem for sensing in aqueous media unless utilizing resonant phenomena [2–4] or high-index coatings [5] in microstructured fibers. Microstructured fibers [6] are promising platforms for optical sensing [7,8], but they are not immune from the problems described above. It has previously been shown in the context of integrated planar waveguide structures that an effective alternative approach is to use the analyte to modify the coupling between two or more identical waveguides [9]. This approach has the additional advantage of modulating device transmittance with analyte index through interference between the supermodes of the structure, providing a simple and robust interferometric sensing platform. Here we demonstrate a similar approach to refractive index sensing in microstructured optical fibers, and we show that by appropriate choice of parameters the device may be designed for either low or high sensitivity; we also show that a single device could in principle be used over a wide range of analyte index.

Refractive index sensing by using the analyte to modify the coupling between two cores in refractive index guiding microstructured fiber was recently demonstrated by Wu *et al.* [10]; however, in that work the analyte channel formed one of the waveguides, and the sensing characterisic was derived from the phase matching of dissimilar waveguides. Consequently, although the device demonstrated high sensitivity, it was useful only over a narrow range of analyte indices and was restricted to measuring analyte indices higher than the silica host.

Microstructured optical fibers are particularly well suited to fabrication of multicore structures incorporating coupled waveguides [11,12], and structures in which coupling occurs between refractive index guiding cores have been well analyzed [13–15]. It has

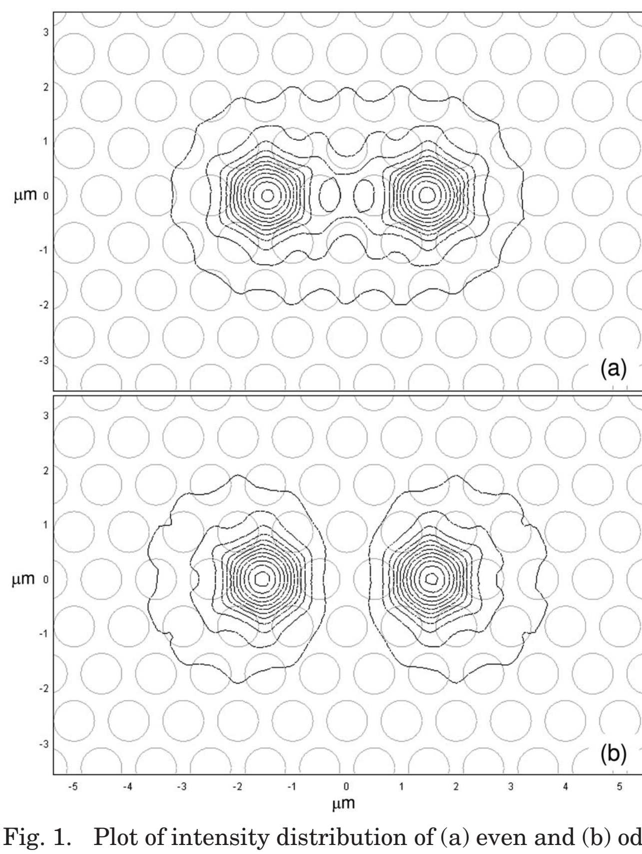


Fig. 1. Plot of intensity distribution of (a) even and (b) odd supermodes at $\lambda = 633$ nm in a dual-core microstructured fiber with hole diameter $d = 0.750\ \mu$m and hole pitch $\Lambda = 1\ \mu$m. The refractive index of the host is $n_{\text{host}} = 1.45$, and all holes are assumed to be filled with an analyte with refractive index $n_a = 1.42$. The horizontal and vertical scales are in micrometers.

 

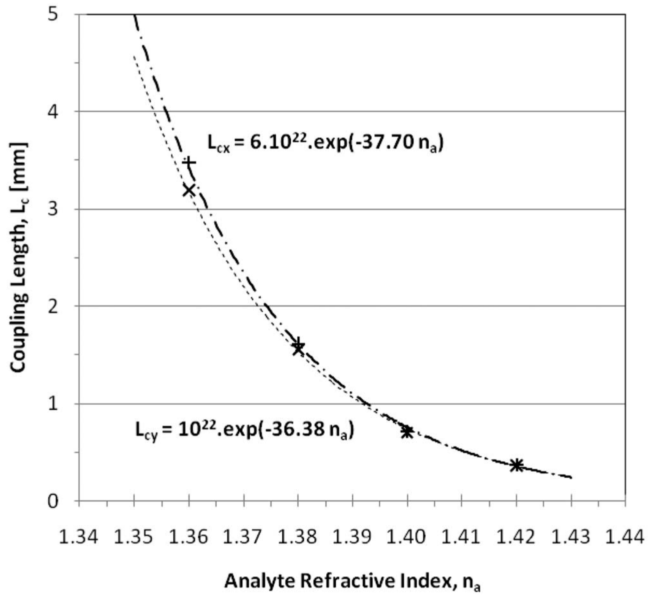


Fig. 2. Plot of coupling length versus analyte refractive index when all holes in the microstructure are filled with analyte: +, input polarization vertical; ×, input polarization horizontal.

been shown that for a range of parameters in which they behave like ideal step-index coupled waveguides there is an exponential dependence of coupling length, $L_c$, on normalized frequency, $\Lambda/\lambda$, and effective NA (i.e., where $\Lambda$ is the pitch of the structure and $\lambda$ is the free-space wavelength), although the step-index model breaks down at short wavelengths [14].

The dual-core sensing structure proposed here is shown schematically in Fig. 1. The solid cores (in this case two) are separated by a number of holes in the microstructure (in this case two). The structure was modeled using commercially available finite-element software (FemLab) and was designed to be single mode in each core at a wavelength of $\lambda = 633$ nm, with a host refractive index $n_h = 1.45$ (i.e., approximately the refractive index of glass or polymer), and analyte refractive index $1.3 < n_a < n_h$. The resulting structure was based on a triangular lattice of holes with diameter $d = 750$ nm and hole spacing or pitch $\Lambda = 1000$ nm.

We considered two methods of use, i.e., in which (i) all holes are filled with analyte, and (ii) only the holes separating the solid cores are selectively filled with analyte. Practical aspects of filling microstructured fibers with analyte have been discussed by Kuhlmey *et al.* [16]. In both cases the dual-core fiber behaves as an interferometer for the odd and even supermodes of the coupler. The device gains its sensitivity from the fact that only one supermode has substantial overlap with the analyte [compare Figs. 1(a) and 1(b)] and has the additional advantage that the refractive index of the analyte directly modulates the device transmittance (i.e., over a given length at a given wavelength) by its differential influence on the effective index of the two supermodes [4,9].

Figure 2 shows the coupling length between the two cores as a function of analyte refractive index when all holes in the microstructure are filled with analyte. This configuration is simplest to implement, as it does not require selective filling. The change in coupling length was approximated analytically by an exponential function, which was then used to derive the transmittance characteristic (i.e., output power relative to input power) as a function of analyte refractive index in a 2-mm-long device, shown by the dotted curve in Fig. 3. As seen in Figs. 2 and 3, when the analyte index is low the two cores are weakly coupled; however, the coupling length (and hence the fringe spacing in the transmittance characteristic) decreases exponentially with increasing analyte refractive index. The latter is a result of the approximately exponential variation of overlap integral of the modes of the two waveguides.

Assuming the device is biased to a point of maximum sensitivity (i.e., 50% transmittance), the decreasing spacing of the transmittance fringes is accompanied by an increasing sensitivity to changes in analyte index. For example, for the device shown the change in transmittance is 32,182%/RIU [i.e., percent change in transmittance relative to unity per refractive index unit (RIU)] when the analyte index is around $n_a = 1.42$, i.e., 1 order of magnitude larger than the sensitivity when $n_a \sim 1.36$. Note that for detecting changes in refractive index the device could readily be biased to the point of 50% transmittance by adjusting either the device optical path length (e.g., by thermal tuning) or by fine tuning the source wavelength. (N.B.: The device transmittance is also expected to be highly sensitive to changes in temperature and/or source wavelength; however, a general sensitivity calculation is beyond the scope of this short communication).

It should also be noted that the aperiodic fringes in the transmittance characteristic provide the potential for absolute refractive index measurements over

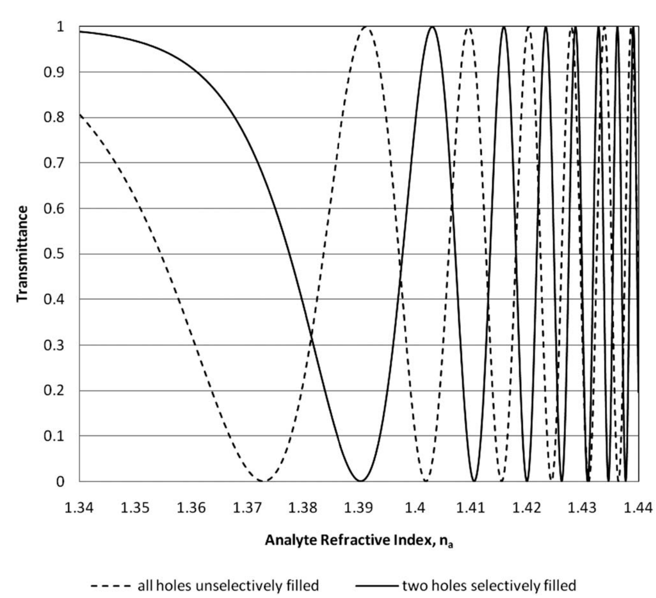


Fig. 3. Plot of transmittance of a 2 mm length of the dual-core sensing fiber for vertically polarized input as a function of analyte refractive index for (i) all holes nonselectively filled with analyte (dotted curve) and (ii) only the two holes between the cores selectively filled with analyte (solid curve).

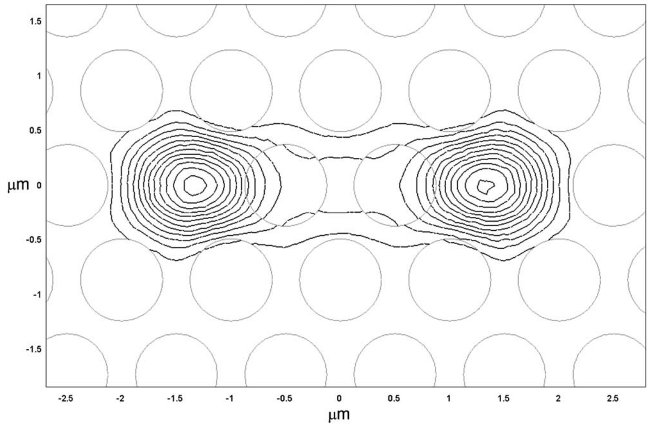


Fig. 4. Plot of the intensity distribution of the even supermode in the same structure as shown in Fig. 1, except for selective filling of only the two holes between the two cores with analyte (all other holes are assumed air filled). The horizontal and vertical scales are in micrometers.

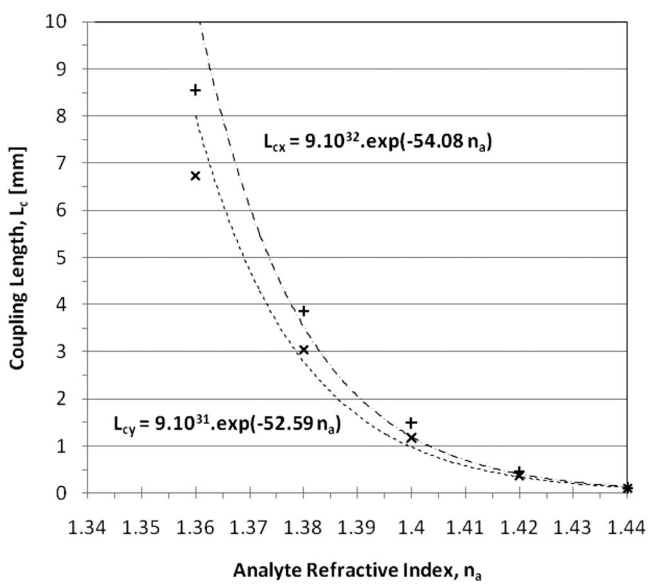


Fig. 5. Plot of coupling length versus analyte refractive index in the selectively filled microstructure. +, input polarization vertical; ×, input polarization horizontal.

a wide range in the one device, as each point on the transmittance characteristic has a unique combination of transmittance and transmittance slope. The latter feature would require two measurements rather than one but clearly distinguishes coupled waveguide interferometers from Mach–Zehnder and other interferometers that are sensitive to changes in the propagation constant relative to an isolated reference path and produce periodic interference fringes.

Sensitivity of the device may be increased in one or more of the following ways: (i) increasing the fiber length (sensitivity scales with fiber length), (ii) reducing the number of holes between the two cores (at the expense of reduced analyte index range), or (iii) selectively filling only the holes between the cores with analyte [16]. Results of the last approach are shown in Figs. 3–5. In Fig. 4 it can be seen that selective filling increases the confinement of the light to the analyte, thereby substantially reducing the device coupling length, as shown in Fig 5. The solid curve in Fig. 3 is the resulting transmittance characteristic obtained by approximating the coupling length as an exponential function of analyte index. Around $n_a = 1.44$ the sensitivity of the device is 167,911%/RIU, i.e., several times larger than without selective filling, and greater than the sensitivity reported by Wu *et al.* [10].

In conclusion, we have shown that microstructured fibers in which the analyte modifies the coupling between coupled cores can have a number of advantageous properties for refractive index sensing, including simple system design, high or low sensitivity depending on fiber parameters, and the potential for use over a wide range of analyte refractive index.

This work was supported by the Australian Research Council and the Danish Agency for Science Technology and Innovation.

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