Interdisciplinary Applications of Optical Fibers

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Abstract: Optical fibers have been used in the field of communication widely. They have also seen their implementation in the medical field. In this paper we shall see the interdisciplinary feature of optical fibers. Applications such as the tunable micro-fluidic optical fiber and photo-acoustic spectroscopic gas sensing with the use of optical fibers is discussed in this paper.

Keywords: Optical fibers, Micro structured , Micro-fluidic, Tunable optics , Long Period Grating (LPG), Spectroscopy, Photo-acoustic, Micro-electro-mechanics.

I. INTRODUCTION

Optical fibers are the core components of fiber optics. They are a kind of waveguides, which are usually made of some kind of glass, can potentially be very long (hundreds of kilometers), and are in contrast to other waveguides – fairly flexible[4].

The science and technology of optical fiber has recently become the focus of intense research interest, driven in part by the development of new types of fibers that incorporate interior microchannels. These microstructured fibers can exhibit novel optical properties, such as photonic band gap guidance and super-continuum generation. An approach for making these and other types of specialized optical fibers tunable by introducing composite or multiple fluid plugs into the microchannels [3] is presented in this paper. Pumping[2] these plugs to different locations along the fiber and adjusting their optical properties provides a flexible means to control the optical waveguiding characteristics of the fiber. This area, which we refer to as micro-fluidic fiber (μFF) optics, is particularly interesting because it demonstrates the feasibility of integrating advances in micro-fluidic designs and analysis into the area of fiber optics. It further provides a route for making the fiber itself a reconfigurable and ‘active’ network component[2].

Also, Optical fiber technology is playing an increasingly important role in environmental and safety monitoring, as well as chemical and biological sensing. They are based upon different sensing mechanisms such as absorption, Raman scattering, fluorescence, surface plasmon resonance, and mechanical-deformation caused by gas-material interaction. There are pros and cons associated with sensors based on different mechanisms. This paper also discusses fiber sensors photo-acoustic spectroscopic principles, which have been studied extensively recently for its simplicity, high sensitivity, multiplexing capability, and greater potential for field applications[1].

II. TUNABLE MICRO-FLUIDIC OPTICAL FIBER

A cross section of the microstructured fiber that is used is shown in Fig. 1. This fiber supports a single mode that is confined by total internal reflection at the core/cladding interface, and which does not interact with the channels [2]. The micro-fluidic plugs can be loaded by capillary action, and positioned to a desired location along the fiber, either by applying a vacuum or by allowing the plugs to drain through the channels under the action of gravity. Fusion splicing is used to provide low-loss (~0.1 dB) optical coupling of the microstructured fiber to standard single-mode fiber. The channel collapse and fusion bonding associated with the splice provides both a hermetic seal and the basis for a robust mechanical joint; it also traps the imbibed fluid plugs between two segments of air-filled channels. Pressurizing one of these two air segments (for example, by increasing its temperature) drives the plugs to a new equilibrium position along the fiber; if the pressurizing mechanism is deactivated (for example, by allowing the heated air to cool), back pressure in the ‘opposing’ air segment drives the fluid to its original equilibrium position. This and other pumping techniques can be combined with methods to change the intrinsic optical properties of the fluids (e.g., their refractive index) to achieve a dynamic and flexible system for controlling the transmission characteristics of the fiber. To accomplish this goal, light in the core, which does not interact with the channels, is coupled at well defined spatial positions to modes whose intensity distribution has significant channel overlap. The fluids can then control the transmission characteristics by altering portions of the refractive index profile that are relevant to these modes[2].

Figure 1: A cross section of the microstructured
Fig. 2 illustrates the calculated core mode intensity distribution in the microstructured fiber. To bring this mode field into interaction with fluids in the channels, a long-period grating (LPG) written in the fiber core is utilized [2].

An LPG[3] induces phased-matched coupling of the core mode to a forward-propagating mode that involves significant intensity in the cladding . This coupling produces a narrowband loss feature in the spectrum of transmitted core light. The central position, \( l_{res} \), of this resonance is governed by the phase-matching condition:

\[
l_{res} = (n_{core} - n_{clad})L
\]

where \( n_{core} \) is the effective core mode index, \( n_{clad} \) is the effective cladding mode index, and \( L \) is the period of grating index modulation. The strength of the coupling, \( pg \), which determines the depth of the associated resonance loss, is related to the length of the grating and the magnitude of the index modulation associated with it. If the fiber channels contain a fluid whose index is below that of silica, then the cladding mode is strictly guided by total internal reflection: it is completely confined to the central region of the fiber which is bounded by the interface between the silica and the micro-fluidic channels. which a high-index fluid plug extends over the grating region therefore continuously tunes the strength, \( lgp \), of the LPG-generated resonance. Figures 1(b) and 1(c) indicate the two-component micro-fluidic arrangement in our microstructured fiber relative to an LPG (4 cm long, \( L=500 \) mm) written in the core. The tuning fluids consist of adjacent, 4.5 cm long segments of low (\( n=1.28 \)) and high (\( n=1.73 \)) index immiscible micro-fluidic plugs. The fluids[3] are pulled into the fiber one after another with no intervening air gap and positioned such that the interface between the fluids lies at the edge of the LPG, before the fusion splices to conventional single mode fiber (SMF) are made. Independent thin-film resistive microheaters control the temperature of the grating region (‘‘grating’’ heater; 8 cm long) and the air channels on one side of the dual-fluid plug (‘‘pump’’ heater; 15 cm long). The voltage, \( V_{grat} \), applied to the grating heater sets the temperature, \( T_{grat} \), of fluid residing in the LPG region. \( V_{pump} \) controls the temperature of the sealed air channels to the left-hand side of the dual-fluid plug, and therefore adjusts the overlap of the high-index fluid with the fiber grating. In this manner, \( V_{grat} \) controls \( l_{res} \) and \( V_{pump} \) controls \( pg \), in a nearly independent fashion . This system was characterized by measuring its spectral transmission characteristics as a function of \( V_{pump} \) and \( V_{grat} \).

III. PHOTO - ACOUSTIC SPECTROSCOPIC GAS SENSING WITH OPTICAL FIBERS [1]

Photo-acoustic spectroscopy (PAS)[1] is another important technique that is widely used for trace gas detection . The basic operating principle of a PAS based gas sensor is illustrated in Fig. 3. A laser beam with its intensity or wavelength periodically modulated is delivered to a gas cell within which light energy is absorbed by gas molecules, and an acoustic pressure wave is then generated via the photo-acoustic (PA) effect. The acoustic wave is then detected by a sensitive acoustic transducer or microphone and further data processing is employed to recover the gas concentration. As the detection object in PAS is acoustic pressure instead of optical intensity, gas detection based on PAS would have the following characteristics or advantages:

1. No background signal. The PA signal is proportional to light absorption by target gas, there is no acoustic signal without light absorption.

2. For a specific microphone, the acoustic signal is not significantly affected by the optical path length, as long as the absorption region covers the size of the microphone. This means that extremely compact sensors could be developed with good sensitivity.

In addition, by use of a multi-pass gas cell to increase the light energy absorbed by the gas molecules and/or an acoustic resonator to enhance the accumulation of acoustic energy in the cell, the detection sensitivity may be further improved[1].

A. PA excitation with optical fibers

In early PAS systems, laser beam is coupled into the PA cell via free space optics with bulky collimating/focusing lenses (Fig. 3)[1].

Optical beam should be carefully collimated and focused to a specific region for efficient generation and detection of acoustic wave.
This is especially the case when an acoustic resonator is used to enhance the acoustic detection and precise assembly of the setup is then required and the system is sometimes complicated and cumbersome.

The use of fiber pigtailed collimator lens (Fig. 4) ease the alignment and at the same time allows the delivery of excitation light through the optical fiber. This allows the light source be located remotely from the sensor head and in a well controlled environment. Taking advantage of the EW of a tapered optical microfiber, we demonstrated that the acoustic wave can be generated by the EW of a microfiber, which avoids the use of complicated collimating/focusing optics. With a quartz tuning fork as the acoustic probe, we tested several fiber tapers with different diameters and the normalized noise equivalent absorption coefficient of 1.96x10^-6 cm^-1 W/Hz^1/2 was achieved with a fiber taper of a diameter of 1.1 μm. By reducing the fiber diameter, the power percentage in the evanescent field could be further enhanced, which promises a gas detection sensitivity comparable to that of a conventional open path PAS sensor. In PAS, the generated signal is not determined by the absorption path length but the localized acoustic pressure amplitude and the detection sensitivity of the microphone. Therefore, a micro/nano fiber with a length of slightly larger than the size of the microphone would be sufficient, avoiding the use of a long fiber taper and the problems associated with it.

![Image](50x362 to 286x451)

**Figure 3:** Basic operating principle of a PAS based gas sensor

**B. All-Fiber PAS-based gas sensors**

With fiber-optic delivery of the excitation light and probing of the PA pressure wave, all-fiber PAS based gas sensors may be developed. A minimum detectable acetylene concentration level of 1.56 ppb was achieved by using a fiber laser with wavelength around 1530.37 nm and amplified power of 500mW as the excitation laser, with a polymer-diaphragm-based EFPI operating at the quadrature point of interferometric fringe as the acoustic probe.

In a miniature all-fiber PAS gas sensor, the sensor head comprises a fiber-tip FPI with a thin polymer diaphragm, acting as a PA cell for light-gas interaction, as well as an acoustic probe. To excite PA pressure wave an excitation laser with wavelength λ = 1.53 μm and optical power of 8 mW is delivered to the Fabry–Perot cavity. Also to measure the cavity length variation induced by the acoustic pressure wave a probe laser with wavelength tuned to the linear region of the FPI interference fringe (l_p = 1556.1 nm) and with a power of 4 mW is coupled to the same FPI. Thus with this setup, a minimum detectable acetylene concentration level of 4.3 ppm was achieved corresponding to a minimum absorption coefficient normalized to optical power of α_min.P = 1.07x10^-8 cm^-1 W^-1/2 .

![Image](50x362 to 286x451)

**Figure 4:** Pigtailed collimator lens

**CONCLUSION**

In summary[3], we have demonstrated a multifunctional, all-fiber filter whose independent tuning over a broad range of both transmission wavelength and attenuation is based on the adjustable position and optical properties of composite microfluidic plugs, located directly inside the fiber. Micro-fluidics-based fiber optics is appealing because it combines the advantages of conventional fiber (low loss, mechanical robustness, low cost, etc.) with tuning capabilities that have been traditionally achieved with bulk optics, micro-electro-mechanical systems, or planar waveguide devices. For PAS-based gas sensors[1], very high sensitivity of the order of ppb has been experimentally demonstrated. Attempts are being made to develop practical fiber-optic acoustic probes and interrogation units, with which all-fiber PAS-based gas sensors may be developed as well as lower cost PAS-based multiplexed or distributed gas sensor networks.

**References**


