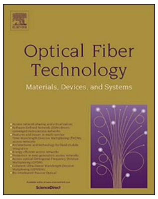
Optical Fiber Technology 41 (2018) 82–88

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte



Studies of geometrical profiling in fabricated tapered optical fibers using whispering gallery modes spectroscopy

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ARTICLE INFO

Keywords:
Fibers
Fiber optics sensors
Microcavity devices
Microstructured optical fibers
Resonators
Surface waves
Fiber characterization
Fiber properties

ABSTRACT

This paper experimentally demonstrates a method for geometrical profiling of asymmetries in fabricated thin microfiber tapers with waist diameters ranging from ∼10 to ∼50 μm with submicron accuracy. The method is based on the analysis of whispering gallery mode resonances excited in cylindrical fiber resonators as a result of evanescent coupling of light propagating through the fiber taper. The submicron accuracy of the proposed method has been verified by SEM studies. The method can be applied as a quality control tool in fabrication of microfiber based devices and sensors or for fine-tuning of microfiber fabrication set-ups.

1. Introduction

Precise measurement of the outside diameter of standard optical fibers is important in both the manufacturing and quality control of such fibers. Fiber diameter measurements are used to understand and dynamically control the fiber drawing process and to select fibers suitable for commercial use. Other areas where a highly accurate fiber diameter measurement technique is required are related to improving the quality of fiber Bragg gratings [1], fabrication of special fibers, fiber-based devices, and more recently, microfiber based resonant devices [2].

Many of the fiber diameter measurement techniques developed to date are based on an analysis of interference fringes or diffraction patterns produced as a result of light scattering by an optical fiber under test [3–11]. The accuracy of these techniques is in the order of a few tens of nanometers, but complex equipment is required utilising spatial optics which involves complex measurement and signal processing. Birks et al. [12] suggested a simple and accurate method for the measurement of the variations in the diameter of an optical fiber based on the use of a microfiber. In their experiment, a guided mode of a microfiber was evanescently coupled into whispering-gallery modes (WGMs) propagating around the circumference of the fiber under test, which itself served as a cylindrical micro-resonator.

WGMs are electromagnetic surface oscillations which arise in dielectric micro-resonators with a circular structure as a result of the trapping of light within the micro-resonator by total internal reflections from the resonator's curved surface with a near-glancing incidence (angle of incidence (i) ∼90°) [13]. Such reflections force the light to take on a polygonal path within the curved structure, very close to the surface of the resonator, and effectively confine its energy within very small volumes. The exceptional sensitivity of such resonances to the shape and size of the resonator make WGM spectroscopy a promising tool for geometrical profiling that can measure diameter variations at a sub-wavelength scale.

In Birks's experiments a microfiber with a guided light mode was used to accurately measure the relative diameter variations of less than one part in 10^4, as a possible means to implement accurate diameter control for fiber drawing. In that scheme, the microfiber and fiber under test moved relative to each other and were also in physical contact with each other. The fiber under test acted as a cylindrical WGM resonator and the fiber diameter variation was calculated from the shift of a WGM resonance detected in the transmission spectrum of the microfiber. This technique was further developed by Sumetsky and Dulashko in [14] by addressing some problems in Briks's method that arose because only a single resonance was tracked. This problem was resolved in Sumetsky's method by increasing the number of WGM resonances whose spectral positions were traced leading to the demonstration of reliable angstrom fiber diameter measurement accuracy.

Another alternative method of fiber characterization is by calculating the effective diameter of the resonator using the information from the WGMs spectral spacing. The fundamental WGMs are localized close to the surface of the cylindrical resonator and thus the FSR can be

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https://doi.org/10.1016/j.yofte.2018.01.007
Received 25 July 2017; Received in revised form 25 November 2017; Accepted 7 January 2018

linked to the microresonator's effective diameter [15,16]. Using this approach, Boleininger et al. [17] experimentally demonstrated WGM profiling of a 3 mm long tapered optical fiber with a diameter > 80 µm, and verified the accuracy of their method using optical microscopy data.

Tapered optical fibers themselves have been intensively studied in the recent years for applications as sensors for temperature, strain and biomedical measurands as well as various devices for optical communications due to their simple fabrication, configurability and excellent performance [2,18–21]. More recently asymmetric fiber tapers have attracted a lot of attention as high sensitivity sensors, narrow-line optical comb filters [22–25] and surface nano-scale axial photonics devices [26–29]. The growing popularity of tapered fiber based devices requires the development of a simple and accurate taper profiling and a-/symmetries characterization method which would be useful for better understanding of such devices fabrication and quality control.

In this paper, we for the first time explore and experimentally demonstrate applicability of WGM spectroscopy for characterization of asymmetries in thin fiber tapers with waist diameters ranging from ~10 to ~50 µm where a submicron resolution is required.

Our WGM spectroscopy method is based on calculations of effective diameters using the experimentally measured FSR of the WGMs spectra. The technique is nondestructive and the measurements can be carried out *in situ* as opposed to measurements with an optical microscope. In addition, the proposed technique is a better alternative to optical microscopy since its resolution is not limited by the diffraction limit. To verify the submicron accuracy of our proposed method effective diameters of the tapered fibers calculated using the WGM spectroscopy were verified by scanning electron microscopy (SEM).

2. Theoretical background

2.1. Tapered fiber transmission spectra

The transmission characteristics of a tapered optical fiber, coupled with a cylindrical micro resonator and the coupled power circulating inside the cylindrical micro-resonator, can be described using universal coupled microcavity theory [30]. In Fig. 1, the field amplitudes at the input and output of the tapered optical fiber are denoted as a_1 and b_1 respectively.

The coupled field amplitudes in the cylindrical micro-resonator immediately before and after the coupling region are a_2 and b_2 respectively. The circulation loss factor inside the cylinder is denoted by α, which can be found from [30]:

$$\frac{a_2}{b_2} = \alpha e^{i\theta} \tag{1}$$

where θ is the circulation phase shift given by:

$$\theta = \frac{4\pi^2 R n_{eff}}{\lambda} \tag{2}$$

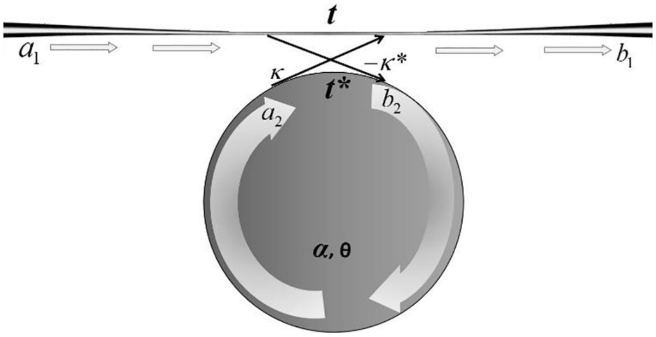

Fig. 1. Schematic diagram of tapered fiber coupled cylindrical resonator.

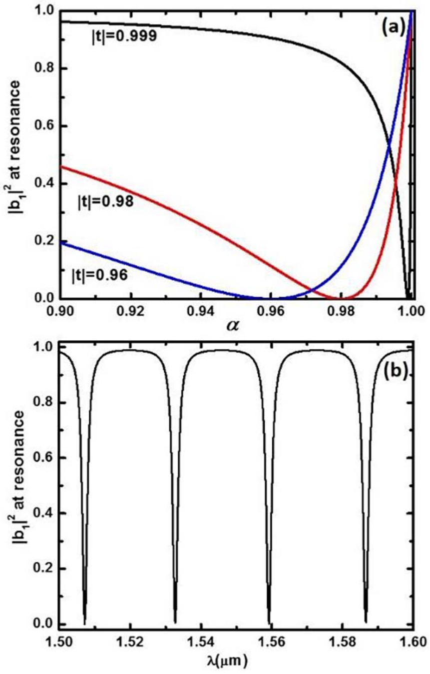

Fig. 2. (a) Relationship between the transmission power of the tapered fiber coupled with the cylindrical microresonator with the resonator internal loss coefficient (α) and, transmission loss coefficient (|t|) with its transmission power. (b) The simulated transmission spectrum of the tapered fiber at critical coupling.

Here n_{eff} is the effective refractive index of the mode that propagates along a circular path within the cavity, R is the radius of the cylindrical micro-cavity, and λ is the resonance wavelength.

By setting $a_1 = 1$, the normalized transmission power of the tapered optical fiber is given by [30]:

$$|b_1|^2 = \frac{\alpha^2 - 2\alpha|t|\cos(\theta-\varphi_t) + |t|^2}{1 - 2\alpha|t|\cos(\theta-\varphi_t) + \alpha^2|t|^2} \tag{3}$$

Here t represents the transmission coefficient of the system, which is related to the coupling coefficient (κ) by the equation:

$$|t|^2 = 1 - |\kappa|^2 \tag{4}$$

where φ_t is the phase offset due to coupling to the tapered optical fiber. When the resonance condition is satisfied, φ_t is zero [31].

Based on Eq. (3), the typical curves of the loss factor (α) due to circulation versus transmission power for a cylindrical resonator-tapered fiber system are simulated and shown in Fig. 2 (a). The simulated plots are for three different values of $|t|$ equal to 0.999, 0.980, and 0.960 respectively. From Eq. (3) it can be seen that when $|t| = \alpha$, there is no light power in the transmission spectrum ($|b_1|^2 = 0$). This is due to the fact that when the internal loss is equal to the transmission loss there is a perfect destructive interference in the tapered fiber between the power transmitted through the fiber taper and the circulating power leaked from the cylindrical resonator. This condition is referred to as the critical coupling [30].

For illustration purposes, Fig. 2 (b) shows the simulated transmission spectrum of the tapered fiber (based on Eq. (3)) coupled with a 20 µm diameter cylindrical micro resonator at critical coupling by setting both the cavity's internal loss coefficient (α) and the transmission loss coefficient ($|t|$) equal to 0.90.

2.2. Effective radius of the resonator and the FSR of its WGM spectrum

A simple approximation can be obtained for the FSR from the propagation constant and neglecting the wavelength dependency of the refractive index [15,16].