Optics Communications 368 (2016) 63–67

Contents lists available at ScienceDirect

Optics Communications

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

Investigation on spectral response of micro-cavity structure by symmetrical tapered fiber tips

Yan Liu [a,*], Yang Li [b], Xiaojun Yan [a], Weidong Li [a]

[a] Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China
[b] Institute of Applied Physics and Computational Mathematics, Beijing 100094, China

ARTICLE INFO

Article history:
Received 2 November 2015
Received in revised form
26 January 2016
Accepted 28 January 2016

Keywords:
Tapered fiber tips
multibeam interference
Fabry–Perot micro-cavity

ABSTRACT

We proposed and experimentally demonstrated a micro-cavity structure made of symmetrical tapered fiber tips. The waist of a conventional fiber taper fabricated from heating and stretching technique is symmetrically cleaved, and the aligned fiber tips with air gap constitute a Fabry–Perot micro-cavity due to the reflection at the tip facet. The spectral responses of such micro-cavity structure have been investigated both in beam propagation models and experiments. The multibeam interference in the micro-cavity and the impact of the waist diameter and cavity length on the spectral response has been successfully demonstrated. And a micro-cavity structure with 45 μm waist diameter was experimentally achieved, the measured spectra agree well with the simulation ones, indicating that the spectral response of the micro-cavity structure is contributed by both the multibeam interference and the Fabry–Perot micro-cavity.

1. Introduction

The tapered fiber tips are of great interest in scientific researches and also have a wide range of applications in areas such as integrated optics [1], microstructural fiber-optic sensors [2–5], near-field optical microscopy [6,7], optical tweezers [8,9], and optical coherence tomography [10] etc. Benefiting from the micro- or nanoscale size, tapered fiber tips provide compact, easy-handling and high resolution detection. Tapered fiber tips are usually fabricated by the heating and stretching technique which employs a gas flame to heat the fiber and computer-controlled high resolution translation stages to clamp and stretch the heated fiber. Similarly, arc discharge or laser beam irradiation may also be alternative to soften the silica fiber. Besides, chemical etching, polishing and laser micro-machining can be used to fabricate tapered fiber tips with desired shape and profiles as well. Typically, the parabolic-like profile is formed due to the surface tension of the fused silica when the heated fiber is drawn with “fast stretching” until it breaks at the waist point [11]. The diameters of the core and cladding in the tapering zone decrease gradually by the same proportion. And linear (conical) tapered fiber tip could be produced by chemical etching [1,4]. Among these methods, however, the tapering utilizing commercial fusion splicer is the most simple and cost effective. The fiber is sharpened to the designed waist diameter with appropriate discharge current, discharge duration and stretching distance. And fiber tips are obtained from high precision cutting of the fabricated taper by either fiber cleavers or ultrafast lasers. The length of the fiber tip fabricating by heating and stretching could reach to several hundred microns. In such kind of tapered fiber tips, guided cladding modes could be generated and multibeam interference will occur accordingly. While for the tapered fiber tip made by etching or polishing, the tip is typically compact in size and about several tens of microns long. The great change of focusing properties in such tips can be used for high spatial resolution sensing [4,12,13]. Fiber tapers fabricated by a fusion splicer are nonadiabatic and have a maximum length limited by the speed and travel distance of the fusion splicer clamps. But the taper cutting introduces the simplest way of profile control of the remained tapered fiber tip. The fiber taper has a uniform waist sandwiched by two transition zones, various shape of tapered fiber tips could be achieved by moving the cutting position along the fiber taper.

The comblike transmission spectrum from a tapered single mode fiber tip is firstly reported in 2008, a cleaved SMF is located in front of the fiber tip as a probe to measure its near-field optical properties [11]. The multibeam interference from the cladding modes contributes to the comblike transmission spectrum. And tunable ring laser is realized by such tapered fiber tip later [14]. In this paper, different from those reports, symmetrical tapered fiber tips manufactured by cleaving the waist of a conventional fiber taper are used to construct a micro-cavity. The tapered fiber tip has an exponential transition region and uniform waist [15]. The

* Corresponding author.
E-mail address: yanliu@bjtu.edu.cn (Y. Liu).

http://dx.doi.org/10.1016/j.optcom.2016.01.080
0030-4018/

near-field and far-field optical intensity distributions and the optical field propagation in the fiber tip with different waist diameters are analyzed numerically by BPM models. And the spectral responses of the micro-cavities with air gap are analyzed numerically and experimentally. Comblike spectra with slowly varying envelopes are observed in the experiments, which can be attributed to the combined effects of multibeam interference and Fabry–Perot interference. Since such kind of fiber cavity is very sensitive, it may find applications in displacement measurement or refractive index sensing and some other fields [16].

2. Micro-cavity structure

The schematic diagram of the fabrication of symmetrical fiber tips combined with fiber tapering and cleaving techniques is shown in Fig. 1. The jacket-off SMF is firstly tapered down to tens of microns, and then a high-precision fiber cleaver cuts the taper waist symmetrically. In the case of vertical cutting, the incident beams would be partly reflected by the tip facets subjected to Fresnel law. Therefore, a micro Fabry–Perot cavity (air gap) is constructed between the facets of two axially aligned fiber tips. It is known that the reflectivity, cavity length and the refractive index of the medium in the cavity completely determine the optical properties of a Fabry–Perot cavity. In the proposed micro-cavity structure with an input field provided from a SMF, the reduction of the core diameter in the fiber tip makes that the fundamental mode that does not satisfy the condition of total internal reflection radiates from the core. The presence of the cladding, however, makes that the radiated modes from the core can still be guided by the fiber. In other words, the fundamental mode in SMF is gradually converted into high-order modes in the first fiber tip [15]. These high-order modes have different effective refractive indices and divergence angles after exiting the fiber tips. Define the reflection from the mirrored ends back to the fiber tips as Type 1 reflection and the reflection from the mirrored ends to the air cavity as Type 2 reflection. In Type 1, the reflectivity is associated with the index of the air cavity, the effective index of the specific mode and the incidence angle of the mode. In Type 2, the reflected field is decided by the overlap of the divergence field and the two fiber tips, which highly depends on the converted mode and the cavity length [17]. Given that, the spectral response of the proposed structure has a close impact on the supported modes in the tip and the cavity length.

At the mode transition region, the fundamental core mode LP_{01} of the input SMF is converted to the LP_{0m} modes of the same symmetry due to the quasi-adiabatic conditions of the mode coupling [18]. The coupling coefficient could be calculated by the overlap integral between field distributions of the fundamental LP_{01} mode and each specific mode. If the waist diameter satisfies the core-mode cutoff condition [19], the waist region supports multimode propagation which results in multimode interference effect [20].

To demonstrate the mode conversion, 3D beam propagation method (BPM) models were constructed with fiber tip parameters given in Table 1. The parameters l_{tr} and l_w represent the lengths of transition and waist regions, respectively. The monitored field distributions with different waist diameters at fiber tip facet and corresponding fields after 200 μm free space propagation are shown in Fig. 2. The field distribution represents the superposition of the converted symmetrical fiber modes [21]. Corresponding to the waist diameter of ~30.5 μm, the cutoff normalized frequency of the SMF estimated from $\sqrt{2/\ln S}$ is 0.853, S is defined as the cladding/core diameter ratio. [19]. In the 80 μm case, the fundamental mode (LP_{01}) is still well-confined in the core region. The

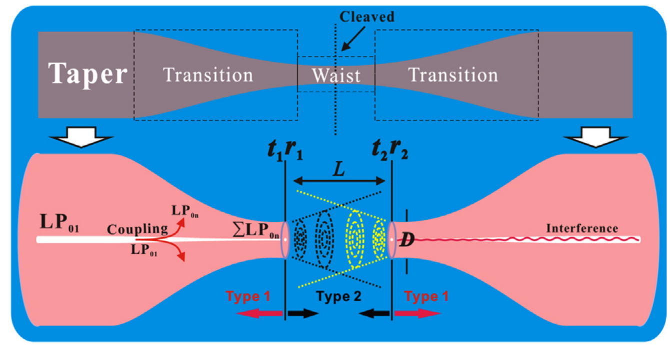

Fig. 1. Schematic diagram of the fabrication of symmetrical fiber tips combined with fiber tapering and cleaving techniques.

Table 1
Parameters used in beam propagation models.

n_{core}	n_{clad}	r_{core} (μm)	R (μm)	λ (μm)	l_{tr} (μm)	l_w (μm)
1.46	1.444	4	62.5	1.55	300	20

divergence field of the 30 μm case is surrounded by a dark ring as shown in Fig. 2(b), which is the evidence of high-order multimode excitation. The core-mode is cutoff and couples to a specific number of radial modes, intuitively, the mode fields at the tip end of 30 μm is larger than that of the 80 μm due to the expand mode profiles. These high-order modes have specific phase relations and converge at periodic longitudinal locations due to the multibeam interference. If the waist diameter further decreases to 10 μm, the core-mode is completely cutoff and the normalized frequency of the multimode region is ~21 at 1.55 μm. And the supported high-order LP_{0n} mode number can be estimated by $M=V/\pi$ [22], so there are 6–7 circular symmetrical modes. This is evidenced by the circular symmetrical field distributions presented in the 10 μm case of Fig. 2(a). The high-order modes typically have a larger divergence angle, therefore, the expand mode field distribution of 10 μm case is much larger than that of the others.

The multibeam interference could be demonstrated by the power monitoring along the propagation. The optical fields (in X–Z plane) of 6 BPM models with varied waist diameters are shown in Fig. 3. And the monitored normalized power as a function of propagation distance for different waist diameters are given as well. The left images have the same horizontal scale as the right one. The curves corresponding to core-mode cutoff cases indicate significant power oscillation, which results from the multibeam interference. In contrast, the normalized power of 80 μm case just follows an exponential decay in the free space propagation. In the 50 μm case the fundamental core-mode is converted to high-order cladding mode in the transition region, however, the core-mode is still dominant. And weak fluctuation could be found around 450 μm of the red curve in Fig. 3.

3. Spectral response

The basic of the proposal is the micro Fabry–Perot cavity formed between the symmetrical tapered fiber tip facets. The interference is similar to that of a conventional Fabry–Perot cavity but with multibeam as the incident source instead of a single beam. The overall effect is that the multibeam interference loads an envelope over the interference fringes of the micro Fabry–Perot cavity. The Fig. 4 shows the schematic diagram of the micro Fabry–Perot cavity with two beams as the source. To simplify the analysis, we only consider two beams here and the divergence angle