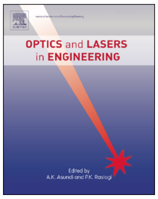
Optics and Lasers in Engineering 74 (2015) 109–113

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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



Curvature investigation in tapered fibers and its application to sensing and mode conversion

Sara Mas*, Javier Martí, Jesús Palací

Nanophotonics Technology Center, Universitat Politècnica de València, Valencia 46022, Spain

ARTICLE INFO

Article history:
Received 26 January 2015
Received in revised form
15 April 2015
Accepted 13 May 2015

Keywords:
Fiber optics sensors
Mode converter
Optical processing

ABSTRACT

Non-adiabatic tapered fibers are basic photonic components used in a wide range of applications. Here we investigate a way to increase their utility through the controllable bending of one of their tapered sections. The experiments carried out explain, for the first time, the mechanics of this approach showing how these tapers can be used to build more sensitive sensors. Their use as highly efficient mode converters is also discussed.

1. Introduction

Tapered fibers are versatile devices capable of carrying out a variety of functions from filtering and light coupling to sensing, among others [1]. They consist of a waist located between two tapered sections which are fabricated through heating and pulling [2,3]. The input mode experiences different effects that depend on the length and shape of the first tapered section. For sections longer than a threshold, which is determined by the characteristics of the fiber, the fundamental mode propagates as usual. These tapers are called adiabatic and its main application is light coupling because of the increased evanescence of the transmitted field [4,5]. However, when the transition between the fiber and waist section is not smooth the fundamental mode couples to higher-order modes that propagate through the waist [6]. Due to the different propagation velocities, an interference pattern is obtained at the output of the device. These are called non-adiabatic tapers and have been used not only in sensing applications [7–9] but also as filters [10–12] and dynamic pulse shapers [13].

Extensive work has been done to observe how different parameters such as the tapered fiber's cross-section profile and waist's radius affect the total response of the device. For example, polarization-maintaining [14] and micro-structured fibers [15,16] have been used to achieve polarization stability thanks to the elliptical core and efficient super-continuum generation due to the increased light confinement, respectively. However, little work has been done to understand how the tapering sections influence the total response. Li et al. reported the detection of curvatures in tapered fibers [17], Sun et al. introduced curvatures on the whole structure to implement an amplitude sensor [18] while Luo et al. presented a micro displacement sensor based on a bent microfiber [19]. Because of the bending of the whole structure the results previously reported are not conclusive with respect to the effect of curving the tapering sections since all of the structure was curved as a whole. We recently reported some guidelines on the manipulation of tapered fibers for their use as refractive index and strain sensors, where the influence of curvatures on the sensor was studied as a whole [20].

In this paper we present the first results that show the effect of small curvatures in one of the tapering regions on the response of the device. The results obtained show that simple geometrical modifications such as mechanical stretching introduce a highly efficient mode conversion that can be used to reconfigure the properties of the device in interesting ways. This can be used to greatly increase its sensing capabilities and to perform lossless mode conversion in only 1 mm of propagation.

2. Principle of operation

Fig. 1 shows the most relevant modes present in a non-adiabatic tapered fiber with waist length L, waist diameter ρ and length of the transition regions L_t. For the geometrical parameters considered here, the fundamental mode splits in two modes, the fundamental cladding mode and a higher order cladding mode. Their different effective indexes originate a spectral sinusoidal fringe pattern at the output of the device due to their different

---

* Corresponding author.
E-mail address: smasg@ntc.upv.es (S. Mas).

http://dx.doi.org/10.1016/j.optlaseng.2015.05.011

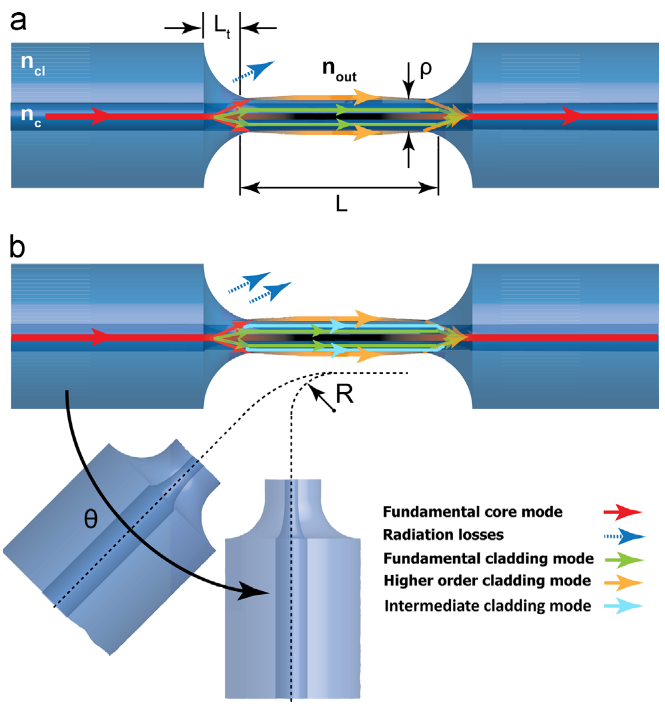


Fig. 1. (a) Straight and (b) curved tapered fiber. n_{cl}, n_c and n_{out} stand for the refractive indexes of cladding, core and outer medium, respectively.

time of arrival. The resulting phase difference between the modes can be expressed as [21]

$$\Delta\phi = \frac{2\pi\,\Delta n_{\mathrm{eff}}\,L}{\lambda} \tag{1}$$

where Δn_{eff} is the effective refractive indexes difference between the two propagating modes, L is the interference length and λ is the operating wavelength. In this case only two modes are generated, although it is clear that the transition regions govern how light splits and combines. One simple geometrical modification consists of introducing a curvature of radius R and arc θ into one of the transition regions. In this case, the refractive index of the tapered fiber depends on the bending radius following the expression

$$n = n_0\left[1+(1+\chi)\frac{x}{R}\right] \tag{2}$$

where n_0 is the refractive index in the corresponding straight tapered fiber, χ refers to the elasto-optic effect and x is the transverse coordinate of the curvature [22]. For radii comparable to the size of the modes, the propagating energy will couple outwards, meaning that the higher order cladding mode will experience increased losses while the fundamental cladding mode will couple to additional cladding modes. This is a simple and efficient way of controlling the number of modes present in the waist and therefore the spectral response of the device. For sensing applications, it can be used to control the amount of light that interacts with the outer medium and to build cheaper sensors that rely on loss measurement instead of monitoring wavelength shifts of the fringe pattern, as in traditional approaches [23].

3. Experimental results and discussion

The experimental setup used to characterize tapered fibers is shown in Fig. 2. A tunable laser, model Santec TSL-210F with a tuning range from 1260 nm to 1630 nm and emitting 0 dBm of optical power in the telecom band and a power meter model Ando AQ2140 were employed to extract the optical response of the device. Two tapered fibers with parameters $L = 13$ mm, $\rho = 18$ µm and $L_t = 1$ mm were fabricated and fixed on translation stages using glue drops before being put inside of a container which was filled with different fluids.

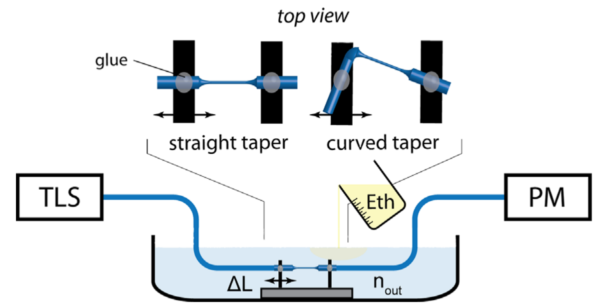


Fig. 2. Experimental setup used to obtain the response of the tapered fibers as a function of strain and outer refractive index. TLS: tunable laser source, PM: power meter.

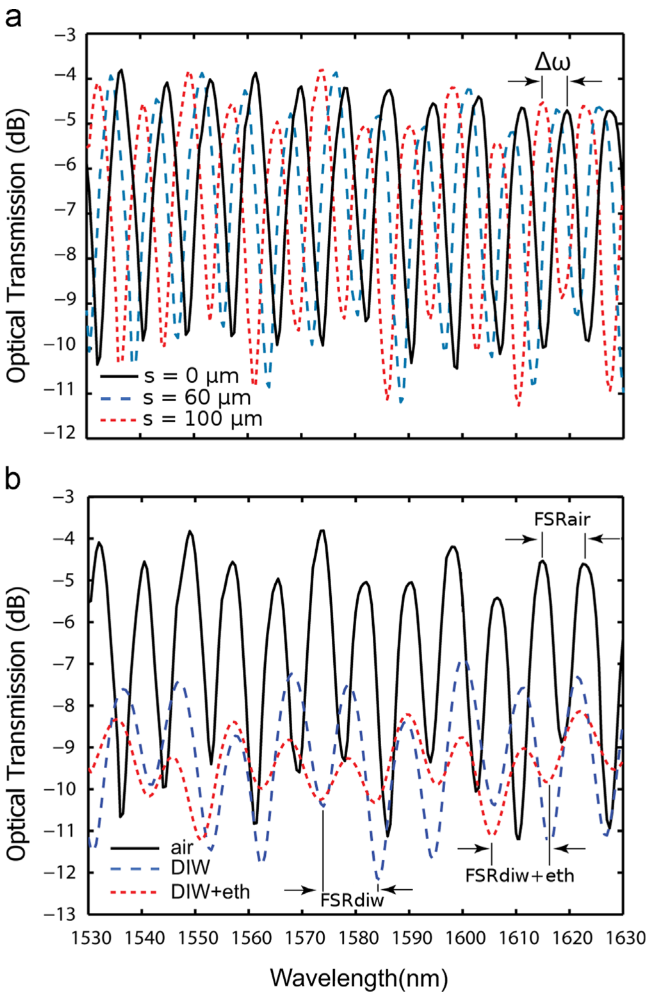


Fig. 3. Spectral response of the straight tapered fiber as a function of (a) strain and (b) surrounding refractive index.

Results for the straight tapered fiber are shown in Fig. 3. A section of 40 mm of fiber that includes the tapered fiber was stretched using the translation stage. Taking into account L and the section-dependent mechanical elasticity of the fiber, approximately half of the stretching applied to the fiber section is applied