Optics & Laser Technology 44 (2012) 1791–1795

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

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

Transmission characteristic of multi-turn microfiber coil resonator

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ARTICLE INFO

Article history:
Received 18 December 2011
Received in revised form
20 January 2012
Accepted 31 January 2012
Available online 2 March 2012

Keywords:
Microfiber coil resonator
Tapered fiber
Flame brushing technique

ABSTRACT

A transmission characteristic of multi-turn microfiber coil resonator (MCR), which is assembled from an adiabatic microfiber, is demonstrated. A comb spectrum was obtained by wrapping a microfiber on a low refractive indexed rod. A resonance with a free spectral range of 0.8 nm was observed with a single turn on a 0.5 mm diameter low-indexed rod and the change in transmission spectrum of the MCR was evident as the number of turns increased. For every additional microfiber turn, there was an addition of an eigenmode to the system which could be observed from the addition of a new resonance for every fringe in the transmission spectrum. The FSR for every added eigenmode was measured to be close to 0.8 nm.

1. Introduction

Microfibers have attracted considerable attention because of their interesting optical properties such as low loss, strong evanescent fields, tight optical confinement, and controllable waveguide dispersion [1,2]. They possess a large refractive index contrast which enables them to provide a tight field confinement which is particularly suitable for nonlinear optical applications [3]. Microfibers also offer an advantage of the ease of integration with conventional single mode fiber (SMF) as well as the access to the strong evanescent field provided by tapering since the light is guided by the boundary between the taper and the external environment [4]. Many research efforts have also focused on the development of microfiber based optical resonators that can serve as optical filters, which have many potential applications in optical communication and sensors [4–7]. One of the powerful microfiber devices is microfiber coil resonators (MCRs) which have a wide range of potential applications such as for optical filters, optical signal processing, slow light generation, sensing and microlasers [8,9]. An MCR is a coiled single-moded optical microfiber wherein the microfiber diameter and the distance between adjacent turns are comparable with the wavelength of the transmitted radiation.

Two types of single coil MCR have been reported in previous literatures: the self-touching microfiber loop resonator (MLR) [1,3] and the microfiber knot resonator (MKR) [4,5]. An MLR is fabricated by coiling a microfiber on itself and keeping two sections of a microfiber together by taking advantage of surface attraction forces (van der Waals and electrostatic). This simple device can be fabricated from a single fiber and thus it has two telecom fiber pigtails at the extremities. A major drawback of the MLR in air is its geometrical stability where coupling is strongly affected by the microcoil geometry and a small change in shape results in a significant change in transmission properties. On the other hand, MKRs have the benefit of a stronger coupling region, but they are disadvantaged in terms of the complexity of fabrication, need to break the microfiber to make a knot and high loss.

In this paper, the transmission characteristic of a multi-turn MCR is experimentally demonstrated. The multi-turn MCR possesses the same functionality as those of an MLR and MKR in optical filtering, lasers and sensors. Additionally, it can be employed as an optical delay line for the optical communication network with high compactness. The MCR is fabricated by winding a long microfiber on a rod coated with a low indexed material. An adiabatic microfiber is obtained by heating and stretching a single mode fiber (SMF) using a flame brushing technique. Since the theoretical analysis of MCRs has been discussed in a number of literatures [2,10], this work concentrates on the fabrication and characterization aspects of this device especially on the investigation of the changes of the transmission spectrum of coil with the turn number and spacing.

2. Fabrication of multi-coil MCR

At first, an adiabatic microfiber was made by heating and stretching the uncoated SMF until the waist diameter was reduced to ~2 μm using a flame brushing technique. A microfiber which is usually about 4–6 cm in length is required so that there is sufficient uniform waist region at the center of the microfiber to assemble

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0030-3992/$ - see front matter © 2012 Published by Elsevier Ltd.
doi:10.1016/j.optlastec.2012.01.035

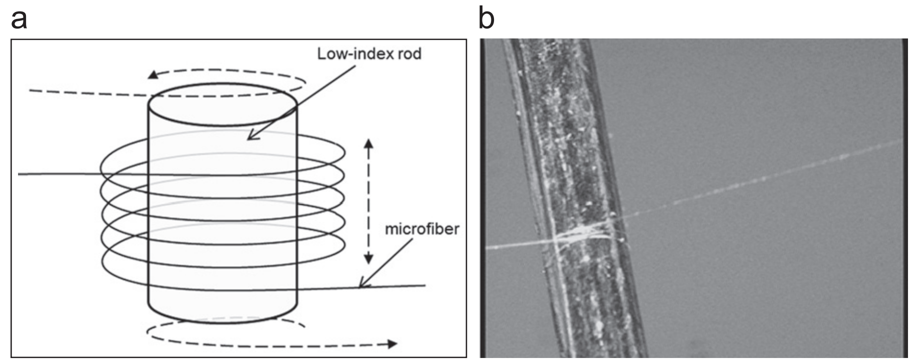

Fig. 1. Helical structure of an MCR: (a) a block diagram showing arrows which indicate the light propagation directions in the resonator and (b) a real microscope image for the MCR wrapped around a low-indexed rod.

a multi-turn MCR [8]. In comparison, an MLR or MKR requires a shorter uniform waist region and thus a 2–3 cm long microfiber is sufficient. The leakage loss of the microfiber is measured to be around 0.2 dB/cm. The MCR was fabricated by wrapping a microfiber on a rod coated with a low indexed polymer (1.36). For microfibers with a large evanescent field or a rod with a high index, it is possible that there are additional losses arising from the leakage loss as the fundamental mode becomes leaky. Generally, the mode is still confined well and the loss is very small when the effective index of the microfiber is bigger than the index of the rod [10]. In winding the microfiber on the rod, the turns of the microfiber are kept as close together as possible to ensure large overlapping area of evanescent fields and strong mode interaction among microfiber turns. In fact, the fabrication is very difficult. The process of winding the microfiber on the rod for more than a single turn is tedious and it requires numerous attempts to achieve a successful MCR.

To ease the microfiber coiling process, the diameter of the microfiber has to be tapered as thin as possible to minimize the elastic force that resists the bending of the microfiber. On the other hand, considering the high insertion loss caused by a long contact length between the microfiber and wound rod, the diameter of the microfiber should be kept above a certain low-bound so that the insertion loss can be maintained at an acceptable level. In our case the maximum value of insertion loss that can be considered is around 22 dB. In practice, the desired microfiber diameter is in the range of 0.8–3 μm [2]. To assist the fabrication of an MCR, a pair of tweezers and a couple of translation stages are required. The windings were done manually by moving the stages in three directions and micromanipulating using tweezers. The close positioning of the microfiber coils was obtained by a combination of manually applied longitudinal tension and gravity. The tweezers are used to help turn the microfiber into a coil and it is important to maintain the cleanliness of the tweezers to minimize contamination to the microfiber during the fabrication process. Fingers should be kept away from the microfiber to prevent deposition of dust or moisture on the microfiber. Fig. 1(a) and (b) shows the block diagram and the real microscopic image of the MCR, respectively. The helical structure of the MCR is supported by a low-refractive indexed rod. The coil structure is rigid and thus it is less affected by the air turbulence compared to an MLR or MKR. Besides propagating along the microfiber, the mode interaction between the microfiber turns allows an inter-turn propagation of light in the forward and backward directions as illustrated by the arrows in Fig. 1(a).

3. Results and discussion

A microfiber loop resonator is the simplest form of an MCR with a single turn. With an increased number of microfiber turns, the resonator has longer length of mode interaction among microfiber turns which consequently allows stronger coupling and produces a more complex transmission spectrum. However, considering the limitation of microfiber fragility, the maximum achievable length of a microfiber and insertion loss, an MCR with a huge number of microfiber turns is impractical. Fig. 2 shows the transmission spectra of an MCR of one, two and three turns wound on a 0.5 mm-diameter low-indexed coated rod. Basically, the optical characteristics of a 1-turn MCR is exactly identical to that of an MLR, where the interference fringes in the MCR transmission spectrum are equally spaced as shown in Fig. 2(a). From the spectrum, the measured FSR is ~0.8 nm and the estimated diameter of the coil is ~0.6 mm which is slightly larger than the rod diameter. It is also observed that the power spectrum before 1533 nm is smooth but the spectrum afterward is increasingly rough. This is due to the noise from the OSA since the ASE power level used is not high enough to support the device loss. When making additional turns to the coil, it is important to ensure that the overlapping or touching between turns establishes coupling between them. For every additional turn made, the transmission spectrum of the MCR is altered. Fig. 2(b), (c) and (d) shows the transmission spectra of a 1-turn, 2-turn and 3-turn MCR fabricated in the laboratory respectively. The pitch between the turns is maintained at around 1 μm to allow the interaction of evanescent fields among turns. Considering the elastic force of the bent microfiber, it is very difficult to maintain the resonance condition while increasing the number of turns at the same time. With the assistance of a microscope, the coiling work was made easier. Nonetheless, the reproducibility of the MCR was difficult and tedious. Compared to other microfiber resonators, MCRs have more complicated light propagation properties [11].

The spectrum of a 2-turn MCR is more complex as compared with that of a 1-turn MCR. It is a combination of two eigenmodes in which the attenuated wavelengths (resonance wavelengths) are labeled (1) and (2) in Fig. 2(b). The two attenuated wavelengths that exist in every fringe are excited by the additional turn of microfiber on the low-indexed rod. The free spectral ranges (FSR) of the spectra in Fig. 2(a) and (b) are evaluated to be around 0.59 nm and 0.84 nm, respectively. The 3-turn MCR has a more complicated transmission spectrum with three attenuated wavelengths labeled as (1)–(3) for every fringe shown in Fig. 2(c). The same FSR is observed for each eigenmode (close to ~0.8 nm) but the difference can be seen from the patterns of fringes (enclosed by two dashed boxes in Fig. 2(c)). The difference is obvious if the two fringes are widely spaced in the transmission spectrum which indicates a small difference in the propagation constants between the eigenmodes. The appearance of additional peaks is observed as an additional turn is added due to the evanescent field coupling among the turns. A regular and uniform