Holey Fiber Microcavities

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Abstract: Microcavities have been formed by placing mirrors on the ends of a short section of holey fiber. The resonant behavior of these devices was analyzed and their suitability for use in nonlinear optics experiments at single-photon intensities was evaluated.

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1. Introduction

Microcavities have played an essential role in cavity quantum electrodynamics (QED) experiments, since their small mode volume and high quality factor (Q) can enhance the interaction between single photons and atoms. More recently, microcavities have been proposed as a method for performing quantum logic operations using single photons as the qubits. For example, we have suggested that microcavities could be used to enhance the performance of Zeno logic gates based on strong two-photon absorption [1-3]. Here we describe some of the preliminary results obtained from a novel type of microcavity that is formed by placing partially reflective mirrors on the ends of a short section of holey fiber.

Most cavity QED experiments require that a single atom or ion be trapped inside a high-Q cavity. One of the potential advantages of the Zeno gate approach is that a large number of atoms can be used instead to produce strong two-photon absorption. The operation of these devices depends on the use of two-photon absorption to inhibit the emission of two photons into the same optical path via the quantum Zeno effect, which would eliminate the intrinsic failure events associated with linear optics quantum logic devices. The rate of two-photon absorption compared to single-photon losses can be enhanced by confining the photons to a resonant cavity with a small mode volume. Since there is no need to trap individual atoms, microcavities of the kind described below could be used with atomic vapors to produce the necessary two-photon absorption.

2. Holey fiber microcavity design

The basic experimental arrangement is illustrated in Fig. 1. A short (21 mm) section of holey fiber was placed between two partially-reflective mirrors to form a resonant cavity. Although other types of holey fibers could be used as well, our current experiments make use of Crystal Fibre NL-15-670 fiber, which has a solid core with a diameter of approximately 1.5 μm surrounded by air cells. When evacuated and filled with an atomic vapor, the evanescent field of the photons in the core can interact with the surrounding atoms.

We are investigating a variety of mirrors for this application, including silvered mirrors as well as dielectric coatings. All of the mirrors were fabricated on microscope cover slips to provide some degree of flexibility when the mirrors are placed in contact with the ends of the fiber. The mirrors were positioned onto the ends of the fiber using motorized translation stages. The reflectivities of the mirrors ranged from 90% to 99% in the initial experiments.

The optical coupling technique shown in the left part of Fig. 1 was used in order to facilitate the placement of the cavity in a vacuum chamber. The output of a conventional optical fiber (SMF830) was collimated using an achromatic doublet lens and then focused onto the end of the holey fiber using a lens with a shorter focal length, which compensates for the difference in numerical apertures of the two types of fibers. The windows of the vacuum chamber will be located in the collimated regions of the input and output beams in order to minimize any distortions. The input and output beams can be focused onto the ends of the holey fiber by controlling the position of the conventional fibers using two sets of three-axis micropositioning systems that were automatically controlled by a computer. The measurements reported here were all performed in air using a frequency-stabilized diode laser operating near 780 nm.

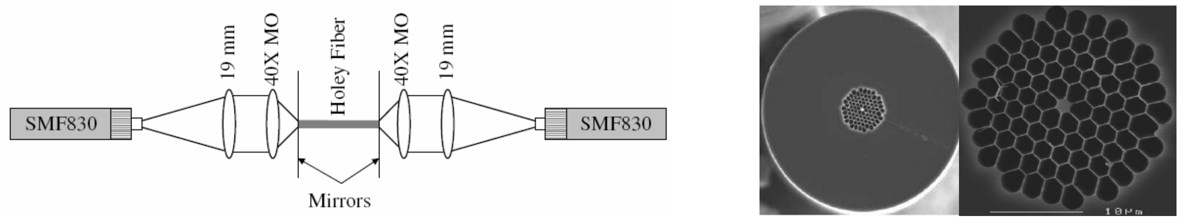

Fig. 1. Basic experimental arrangement used to study a microcavity formed by placing a short section of holey fiber between two partially-reflective mirrors. Two conventional optical fibers are coupled to the cavity using a series of lenses and micropositioners. The structure of the holey fiber is shown in the lower photographs from Crystal Fiber.

3. Results

The quality factors of these resonators ranged from 10^5 to 10^6 and were predominantly limited by losses at the interface between the mirrors and the fiber cavity. In addition to the transmission through the mirrors, loss can occur if the mirror is not aligned perfectly parallel to the end of the fiber or if the fiber cleave is not perfectly flat. This significant source of intra-cavity loss made it impractical to obtain meaningful data for mirrors with reflectivities higher than 90% since the fiber-mirror interface losses increase with each round-trip within the cavity. This source of loss could be mitigated by increasing the length of the microcavity, but increasing the cavity volume would reduce the effectiveness of this device for nonlinear optics or cavity quantum-electrodynamics (QED) experiments.

For experiments with single photons and atomic vapors it is essential to maximize the overlap of the field with the location of the atoms, while at the same time reducing the mode volume. A plot of the theoretical mode volume, defined as the spatial integral over the field intensity normalized to unity at the field maximum, for a cavity of length 1 mm is shown in Fig. 2a for the fundamental mode of holey fiber. The minimum near 440 nm represents the diameter for which the light is most strongly confined at a wavelength of 778 nm. The value of the mode volume at this minimum scales linearly with the length of the cavity. The plot in Fig. 2b shows that this type of fiber has 49% of its power in the air or vacuum at the diameter of peak mode compression, making this an excellent tool for experiments studying the interaction of light with multiple atoms. These diameters could be achieved by heating and tapering the holey fiber, for example.

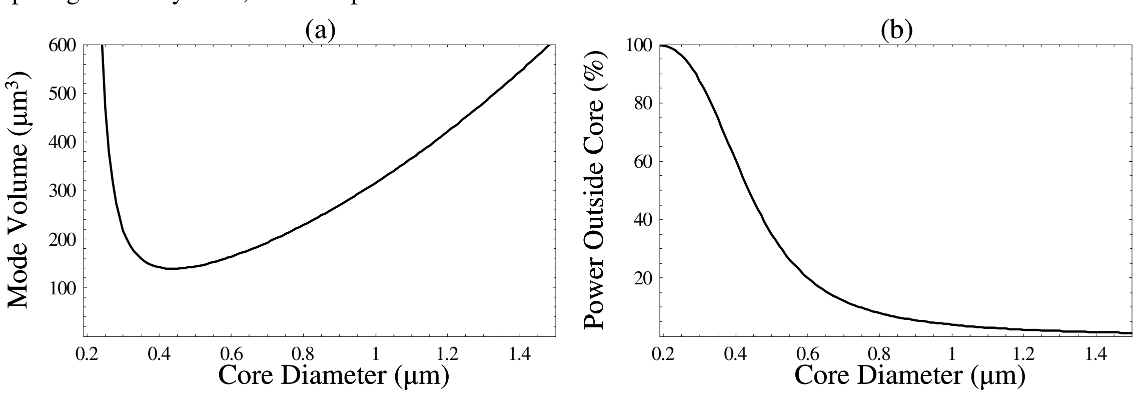

Fig 2. The transverse field distribution can be optimized by choosing the core diameter. (a) The mode volume and (b) the percentage of power guided in air for a cavity of length 1 mm at a wavelength of 778 nm.

4. Conclusion

In summary, we have built and tested a microcavity consisting of a short section of holey fiber with separate end mirrors. This cavity may be a useful tool for investigations of nonlinear optical effects at low intensities, and for QED and quantum logic experiments if the cavity losses can be reduced.

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