Coupling between PhC membrane and lensed fiber: simulations and measurements

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***Abstract*—The Finite Difference Time Domain method and the Mode Matching technique are used to optimize the coupling between lensed-fibers and a waveguide realized on a PhC membrane. Experimental results showing a very good agreement with simulations are presented and discussed.**

I. Introduction

In the last years, photonic crystals (PhCs) have attracted considerable attention because of their effectiveness in controlling the light flow over very small length scales. Various components and applications are predicted and expected to be realized by means of this technology. Although idealistically such components should be realized by means of three-dimensional periodic structures, an alternative solution which uses dielectric membranes with a two-dimensional periodicity, also called 2D PhC slabs, seems very attractive for their relative ease of fabrication.

A lot of active and passive optical components based on PhCs have been designed and realized up to now and their use is expected to grow rapidly in photonic integrated circuits for different applications such as optical telecommunication networks, sensing systems, etc. In these components, optical coupling (consisting of injecting optical signal from fiber into PhCs or vice versa) is one of the major problems that should be taken into consideration.

In this work, simulations including the Finite-Difference Time-Domain (FDTD) method and the Mode-Matching (MM) technique are used to optimize the coupling between a W1 waveguide realized on a PhC membrane and a micro-lensed fiber. Experimental measurements are presented and compared with simulated data. The advantage of using two kinds of micro-lensed fibers in coupling are then discussed.

II. Simulation Approach

Generally, the coupling efficiency is calculated as follow [1]:

$$\eta = \frac{|\iint E_1 E_2^* dxdy|^2}{\iint E_1 E_1^* dxdy \iint E_2 E_2^* dxdy} \quad (1)$$

where E_1 and E_2 are the beam transverse profiles and x, y the transverse coordinates.

The maximum coupling efficiency of the two Gaussian beams occurs when both mode field radius ω_0 (usually called waist), defined at $1/e^2$ of maximum intensity or at $1/e$ of maximum amplitude, are equal and perfectly aligned [2]. A mismatch of mode field radii or a misalignment between the two beams leads to excess losses. The more different the modes are, the higher the losses are. In the case of two identical Gaussian beams, the smaller the mode field diameters, the more critical the lateral and axial positioning tolerances.

The main difficulty in the case of coupling a PhC waveguide to an optical fiber arises from the fact that the mode field radius of photonic crystal circuits are very small (of the order of 0.5 μm) compared to the mode field radius of standard single mode fibers (around 5 μm). Thus, a tapered-PhC-waveguide design is necessary to increase the mode field radius to bigger values. In parallel to tapering the waveguide, the mode field radius of the single mode fiber should be adjusted to fit that of the waveguide. In order to improve the coupling efficiency, either macroscopic objectives [3] or micro-lensed fibers [4], [5] can then be used. Micro-lensed fibers are more interesting because of their compactness and better suited for commercial applications, where installation and packaging play important role for the success of a component.

In this work, we simulate a taper structure for a W1 PhC waveguide which is described in [6]. Results of the FDTD simulation give 0.64 μm for the waist of the transverse mode at the tapered-PhC membrane output (see fig. 1).

This structure is used to numerically evaluate the coupling efficiency with the lowest available lensed fiber waist (i.e. ω_0 = 1.0 μm) and a slightly bigger one (i.e. ω_0 = $1.1 \mu m$) by mode matching technique. Equation (1) is used by replacing E_1 with the above simulated electrical field and E_2 with theoretical circular Gaussian beams. Losses are then deduced which are of 3.6 dB and 4.0 dB for the case ω_0 = 1.0 μm and ω_0 = 1.1 μm respectively.

III. Measurement Results

The mode field profile at the output section of the tapered PhC waveguide are measured in a near field setup by means

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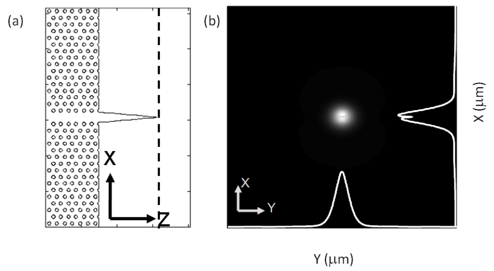

Fig. 1. (a) Top view of the output section of the tapered PhC W1 waveguide. (b) Simulated field mode distribution at the PhC output.)

of an infrared CCD camera (see Figure 2). A high numerical aperture ($NA = 0.95$), antireflection coated objective lens was used. The waveguide is injected from a laser diode by means of a micro-lensed fiber whose mode field radius is around 1 μm at 1550 nm. A variable attenuator was used to avoid power saturation at the camera.

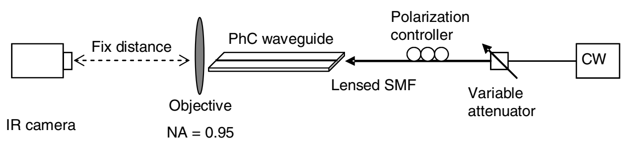

Fig. 2. Near field measurement setup.

The adjustment of coupling is achieved by observing the best focusing of the image captured on the IR camera through the objective lens. The calibration of the mode field radius is achieved by comparing with a micro-lensed fiber whose waist is known to be 1 μm (by far field technique). The distance between the objective lens and the IR camera is fixed for the measurement and calibration so that the magnification is constant. Experimental and simulated near field profiles are plotted in figure 3. We note a good agreement between simulation and measurement results.

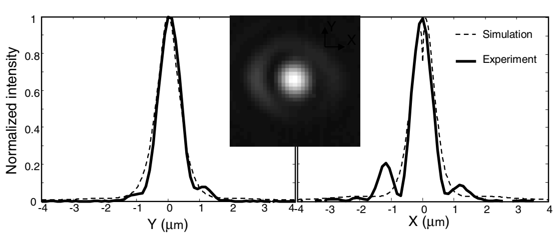

Fig. 3. Experimental(solid line) and simulated (dashed line) near field cross-section profiles. Inset: intensity transverse plane.

The coupling loss are measured with two kinds of micro-lenses, a commercially available Oz fiber (waist 1 μm) and a micro-lens called Gradhyp (waist 1.1 μm) developed at the laboratory [4]. The measurement setup is similar as in Figure 2 except that the objective lens and IR camera are replaced by a lensed fiber. The calculation of coupling loss per face is deduced from the total loss by removing the attenuation of the waveguide, which is taken to be 1 dB/mm. The total loss is defined as A(dB) = -10log(P_{out}/P_{in}). The P_{out} and P_{in} are measured with an integrating sphere connected to an InGaAs power meter. P_{in} is measured at the injection micro-lens output and P_{out} is measured at the end of the receiving lensed fiber.

Using a 1 mm long waveguide, the total loss was 9.4 dB for the Oz fibre and 11 dB for the Gradhyp micro-lens. Therefore, the coupling loss per face is 4.1 dB for the Oz fiber and 4.95 dB with gradhyp micro-lenses, which are very close to the estimated values from simulations.

The main interest of the gradhyp micro-lens when compared to the Oz fiber is not only the tolerance with position mis-alignment, but also the long working distance (defined as the distance between the taper output and the micro-lens output) of 60 μm (compared to 8 μm for the Oz fibre). This can be seen in Figure 4. This long working distance, thank to the wide mode field diameter at the output of the graded index section before entering the hyperbolic profile of the gradhyp micro-lens [4], is of interest for the assembly process, where there is a need to prevent contacts, that could be destructive, between the PhC taper output and the micro-lens.

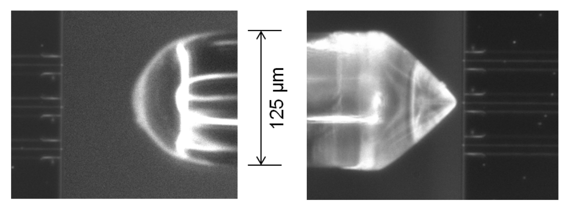

Fig. 4. Pictures of a gradhyp microlens (left) and Oz microlens (right) coupled to a PhC tapered waveguide output (working distance 60 μm for gradhyp and 8 μm for Oz).

IV. Conclusions

A complete FDTD + MM based procedure for the optimized design of the coupling between a PhC W1 tapered waveguide and a micro-lensed fiber has been developed. Results concerning the optimization of these structures have been presented and discussed. Losses as low as 4.1 dB per face have been demonstrated.

Acknowledgment

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