Maximizing On-axis Coupling Efficiency between Single Mode Fiber and Multimode Specialty Fibers Using Multi-Mode Interference

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Abstract: Novel technique to optimize on-axis coupling between single mode fiber and multimode specialty fibers using an intermediate segment of step index multimode fiber is presented. Coupling efficiency of 93% is achieved for optimum fiber parameters.

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1. Introduction

Specialty fibers are widely applied for variety of applications such as light delivery, sensing and biomedical applications. Efficient coupling from a single mode fiber (SMF) source to these specialty fibers is very important. In previous work, this was achieved using external diffractive optical elements [1] or through off-axis coupling. However, for reasons of simplicity and reliability, it is desirable to have an on-axis allfiber coupling scheme. In this work, we present a novel technique to maximize the on-axis coupling between SMF and specialty fibers by inserting a segment of a step index multimode fiber (MMF) between the two fibers as depicted in fig. 1. This segment works as a beam shaping element as will be explained in the following paragraphs.

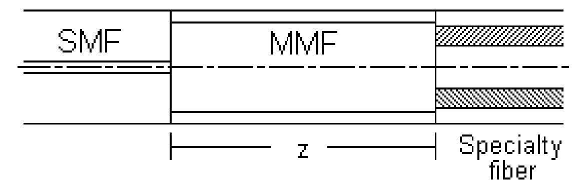

Fig. 1. General structure of the coupling scheme

In fig.1, the approximately Gaussian beam out of the on-axis SMF excites only the first order azimuthal (m=1) modes in the MMF due to its radial symmetry [2]. Each mode gains a different phase while propagating down the MMF. Thus, the total field at any distance z is the superposition of these modes each with a different phase (multimode interference, MMI, effect.) It has been shown that this effect can be used for fiber lensing [2] or displacement sensor [3] applications. In both applications, it was required to have a converging beam out of the fiber. However, here we are using the MMI effect inside the MMF segment to modulate the input field (amplitude and phase) in order to maximize the coupling to the specialty fiber. In other words, the sum of the overlap integrals between the field at the end of the MMF (distance z) and all the guided modes inside the specialty fiber is maximized (ideally goes to 1.)

Due to the phase distribution of the excited modes inside the MMF, only first order azimuthal modes inside the specialty fiber will be excited, which simplifies the required modal calculations significantly. Hence, we first calculate the modal field distributions for the MMF and the specialty fiber. Then, we calculate the source to the MMF modes expansion coefficients, b_n, where n is the MMF radial mode index. Second, we calculate the expansion coefficient for each MMF to specialty fiber mode, $a_{n,h}$ (h is the specialty fiber radial mode index). We can then write the total coupling efficiency, assuming 100% coupling from the SMF to MMF, as:

$$\eta(z) = \sum_{h=1}^{H}\left|\sum_{n=1}^{N}\tilde{a}_{n,h}\tilde{b}_n Exp(i\beta_n z)\right|^2, \quad \tilde{a}_{n,h} = a_{n,h}\sqrt{\frac{P_h}{P_n}} \quad \text{and} \quad \tilde{b}_n = b_n\sqrt{\frac{P_s}{P_n}} \qquad (1)$$

Where, P_s, P_n and P_h are the source power; MMF n^{th} mode power; and the specialty fiber's h^{th} mode power respectively.

2. Results and discussion

In this section we present theoretical calculations for coupling to two specialty optical fibers with ring-shaped guiding regions.

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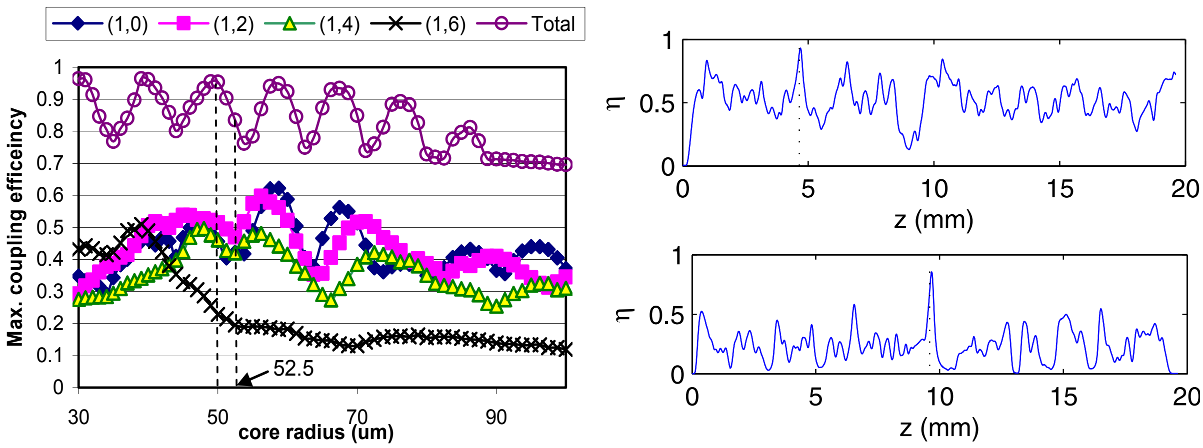
However, the experimental results will be shown in the conference presentation. The first specialty fiber is taken to be a novel multi-shell fiber [4]. The fiber consists of four high refractive index concentric shells of 2.532 µm width and 6.33 µm separations. The inner radius of the first shell is 15.82 µm. These parameters are selected to have a multimode fiber with narrow Bragg response [4]. There are two main MMF parameters to optimize; core radius and segment length. Sweeping over half the re-imaging distance (see ref. [3]) and changing the core radius of the MMF, we obtain the graphs for the maximum coupling efficiency as depicted in fig. 2 (a). The working wavelength is 1.55 µm.



(a) (b)

Fig. 2. (a) Maximum coupling efficiency calculations between SMF and the multi-shell fiber versus the MMF segment core radius. The top graph is the total coupling efficiency. The lower ones are the maximum coupling efficiency to four (out of eight) first order multi-shell fiber azimuthal modes. (b) Top: coupling efficiency between SMF and multi-shell fiber vs. 50 µm core radius MMF segment length (over half re-imaging distance). Bottom: coupling efficiency between SMF and ring GRIN fiber vs. 50 µm core radius MMF segment length.

In these calculations, we used the linear polarization (LP) approximation. The main difference between LP and the full vectorial calculations is a slight shift in the location for maximum coupling and a reduction of the coupling efficiency of approximately 3%. However, it is much faster to use LP approximation in these calculations. The two dashed lines in the graph represent the core radii of 50 µm and the standard 52.5 µm. The maximum coupling efficiencies when using these MMF's are 93% and 80% respectively. For the 50 µm core MMF, using full vectorial modal calculations and applying eq. 1, we obtain the graph in fig. 2(b, top.) It depicts the total coupling efficiency between the SMF and the specialty fiber versus the length of MMF segment. The second specialty fiber is a graded index ring fiber. The graded index parameter is 2.5, the inner radius is 13.35 µm and the core radius is 25.3 µm (the parameters of the real fiber we use for the experimental verifications). Fig. 2 (b, bottom) depicts the calculated coupling efficiency between the SMF and the ring fiber using 50 µm core radius MMF. In Figure 2.(b) the two dashed lines represent the length of the MMF that corresponds to maximum coupling efficiencies between the SMF and the multi-shell and ring fibers. For the multi-shell fiber, a 4.6938 mm segment will correspond to 93% coupling efficiency. However, for the GRIN ring fiber, a 9.681 mm segment of MMF corresponds to 85.6% coupling efficiency. The technique described in this paper is general and can be applied to any combination of specialty and MMF fibers. It only requires the modal and expansion coefficients calculations for the MMF and the specialty fiber used. Then, eq.1 can be used to optimize the fiber parameters. Different fibers will require MMFs with different core radii and lengths for optimum coupling efficiency.

3. References

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