Design of a Tapered Few-Mode Fiber based Broadband Mode Coupler for Multimode OCT

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Abstract: This paper presents a design and simulation study of a tapered few-mode fiber based broadband mode coupler for multimode optical coherence tomography in the O-band for better signal collection efficiency and improved penetration depth.

1. Introduction

Optical coherence tomography (OCT) has been established as a standard-of-care tool for diagnosis of a wide spectrum of ocular diseases, coronary artery disease and gastrointestinal diseases. However, penetration depth and resolution degradation in deep tissue are two major limitations for existing and potential clinical use. For example, OCT is very limited in imaging choroid, sclera and optic nerve head due to limited penetration depth, making it unfit for examining abnormalities in these tissues. In intravascular and endoscopic applications, the penetration limit precludes the technology for assessing deep lesions such as invasive tumors in digestive tracts and large plaques in coronary arteries. In the single mode regime, OCT has reached shot-noise limited detection. Shifting to the multimode regime will make it possible to improve signal collection efficiency by collecting backscattered light from tissue with larger numerical aperture. Previous developments of multimode OCT leverage on the higher order modes interference with single mode reference light, which suffers from crosstalk among different modes [1] [2]. The key to achieve multimode OCT is to efficiently separate signals of different modes into a number of single mode signals before interference with the reference light. More recently, a photonic lantern based on few mode fiber (FMF) to achieve mode-dependent coupling was developed for OCT at 930 nm [3]. FMF has been used extensively in communication applications to augment the transmission capacity and for selective mode couplers [4] [5] [6] . In this paper, we explore the mode selective coupler design based on FMF to separate the higher order signals into single mode signals for multimode OCT in the O band (1.26-1.36 μm).

2. Proposed design

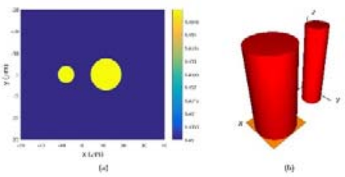

Figure 1: (a) Cross-section of the refractive index profile of the proposed fiber coupler design; (b) 3D view of the fiber coupler. The claddings of both SMF and FMF are not shown in the figure for visualization of two fiber cores only.

The proposed structure is using a tapered few mode fiber (FMF) to lower the effective mode index of the selected higher order mode which can be phase matched to the fundamental mode of the single mode fiber (SMF). The tapered FMF and the SMF are then side polished to reduce the core to core separation so as to achieve efficient mode coupling through evanescent field. The cross section and the 3D view of the proposed design is shown in Figure 1. In this study, the core diameters of the SMF and un-tapered FMF are 8 μm & 19 μm respectively. Both fibers have the same refractive index of the core/cladding, 1.455/1.45. The chosen FMF supports two fiber modes LP_{01} and LP_{11} modes. The coupling of SMF LP_{01} to FMF LP_{01} mode is through direct fusion splicing between both fibers. The material dispersion is neglected in the simulation.

3. Results

In Figure 2 (a), the effective mode indices of the SMF, un-tapered FMF and tapered FMF are plotted. The tapering ratio of the FMF is 0.79, assuming the core diameter is reduced proportionally to the tapering. The LP_{11} mode of the tapered FMF (green dashed line) has very close effective mode index to that of the SMF LP_{01} mode (blue solid line with open circles), suggesting the effective mode coupling in this wavelength range of O band (1.26-1.36 μm). The coupling ratio depends on several parameters, such as the core to core separation, wavelength, and fiber length. The maximum power transfer between two modes is achieved at coupling length L_c, i.e. 14975 μm and 5680 μm for core separation of 4 μm and 6 μm respectively at wavelength 1.26 μm, as shown in Figure 2(b). The power transfer curve at 1.36 μm (purple solid curve) is showing a significant difference in Figure 2(c). For example, the coupling ratio changes from 79.6% to 90.9% at fiber length 4000 μm, and 96% to 79.8% at fiber length 5 mm. Figure 2 (d) shows the o-band coupling ratio for two fiber lengths, with fixed core to core separation of 4 μm. The coupling ratio stays satisfactorily high, i.e. ranging from 79.6% to 92.2% for fiber length of 4 mm, and ranging from 79.8% to 98.8% for fiber length of 5 mm. In addition, for butt coupling of LP_{01} mode in SMF and FMF, the coupling ratio varies from 86.7% to 88.9% as denoted by the dotted line in Figure 2(d).

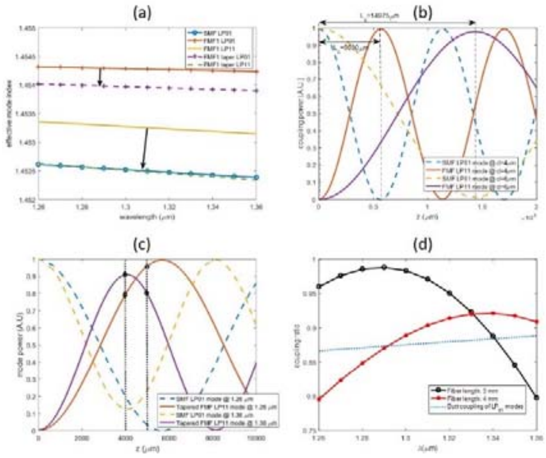

Figure 2: (a) Phase matching of LP11 mode of tapered FMF and LP01 mode of SMF; Mode coupling between the LP01 mode of SMF and the LP11 mode of the tapered FMF (b) for core to core separation of 4 μm and 6 μm respectively, at 1.26 μm; (c) different wavelenths of 1.26 μm and 1.36 μm, with core to core separation of 4 μm; (d) coupling ratio for different fiber length of 4 mm and 5 mm, with core to core separation of 4 μm.

4. Conclusion

Our preliminary simulation results demonstrate that multimode detection in OCT can be efficiently realized using a broadband all-fiber mode coupler. The mode-division detection not only enhances signal strength and improves penetration depth, but also makes it possible to suppress speckle noise by incoherent averaging or compensate for defocus or spherical aberrations through digital refocusing.

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