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Modes Effective Refractive Index Difference Measurement in Few-mode Optical Fiber

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Abstract

We studied the measurement and data analysis of modes effective refractive indexes for few-mode optical fiber and found that measuring refractive index difference from the modes interference pattern was affected by dispersion in the optical fiber. A comprehensive method of accurate measurement of modes effective refractive index differences in few-mode optical fiber was developed. It consists of the measurements of the FBG reflection spectrum and the modes interference spectrum, the simulation of interference with dispersion effect in the interferometer configuration, and the data optimization to match with the measured modes interference. The results show much improvement in the few-mode optical fiber characterization.

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Keywords: modes, effective refractive index difference, few mode fiber

1. Introduction

Few-mode optical fibers have been a hot research area in the past few years. The few mode optical fiber can potentially increase the transmission capacity of a single optical fiber by mode-division multiplexed transmission [1]. The characterization methods and tools for single mode optical fibers are mature; however, the characterization

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of a few-mode optical fiber is much more challenging due to the co-existing of more than one modes than the characterization of a single mode optical fiber.

The effective refractive indices of the modes, and effective refractive index differences between the modes are important characteristics for few-mode optical fibers. By measuring the reflection spectrum of the fiber Bragg grating (FBG) fabricated in the few-mode fiber, some discrete information of effective refractive indices of the modes at their resonance wavelengths can be obtained. However, it can't provide a full view of the modes effective refractive indices across the wavelengths. The interferometer configuration was used to measure the index difference in few-mode optical fibers by some researchers [2][3]. The mode interference in the interferometer configuration caused the intensity change across the wavelengths. Based on the techniques, one could conclude the modes effective refractive index.

Optical low coherence interferometry (OLCI) was proposed for FMF characterization by R. Gabet et al.. The different LP modes could be obtained accurately in a single measurement in combination with a numerical method called "time-wavelength mapping" [4]. Michael A. Galle et al. simultaneously measured first and second order dispersion in short length few mode fibers by using virtual reference interferometry [5]. Multimode dispersion was also measured based on the time-of-flight method [6][7], however, this method couldn't be used for short distance fiber characterization.

In this study, we simulated the interference phenomenon between the modes in few-mode optical fiber, and found that the interference pattern was not only determined by the index difference but also affected by the relative dispersion between the modes. Hence, the method of obtaining refractive index difference from the modes interference pattern is valid only when there is no or minimum dispersion in the optical fiber. We propose a comprehensive method of accurate measurement of modes effective refractive index differences in few-mode optical fiber, consisting of the measurements of the FBG reflection spectrum and the modes interference spectrum, the simulation of interference with dispersion effect in the interferometer configuration, and the data optimization to match with the measured modes interference.

2. Methodology

2.1 Fiber Bragg Gratings

The comprehensive method started with the measurement of the reflection spectrum of a fiber Bragg grating (FBG) fabricated in the few-mode fiber. The few-mode fiber sample is a high Ge-doped Silica optical fiber. The core size of the fiber was about 5 μm. The refractive index of the core and cladding were about 1.49 to 1.44, respectively. Figure 1 shows the index profile of the few-mode fiber. A suitable pitch (530.08 nm) of FBG was chosen so that the reflection peaks by all the modes would be within the wavelength range of 1520 nm to 1620 nm, which range was covered by our tunable laser source and optical spectrum analyzer. Figure 2 shows the reflection spectrum measured from the FBG fabricated in a piece of few-mode fiber sample. There are five peaks in the spectrum. The peaks at the wavelengths of 1575.132nm, 1553.912nm and 1532.76nm correspond to the fundamental mode and the two higher orders modes interacting with the FBG, respectively. The two peaks in between are caused by the coupling between the two adjacent modes in the FBG.

The FBG fabrication process caused slight increase of the refractive index in the fiber. We use the effective refractive indexes calculated from the from the FBG measurement to estimate the effective refractive indexes of the three modes in the few-mode fiber. Figure 3 shows the calculated effective index of the three modes in the few mode fiber from three FBG samples at different pitches. The calculated effective refractive indexes from the three FBG samples form three lines representing the modes across the wavelengths.

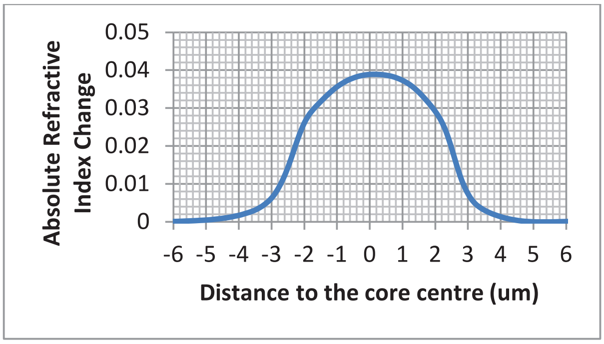


Fig. 1. Refractive index profile of the few-mode fiber.

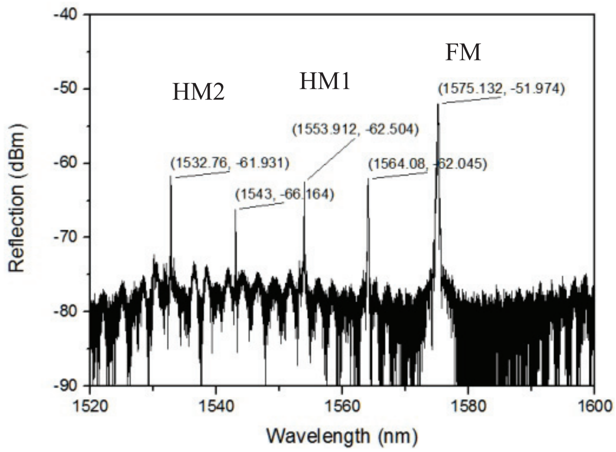


Fig. 2. Reflection spectrum of the FBG fabricated in the few mode fiber sample.

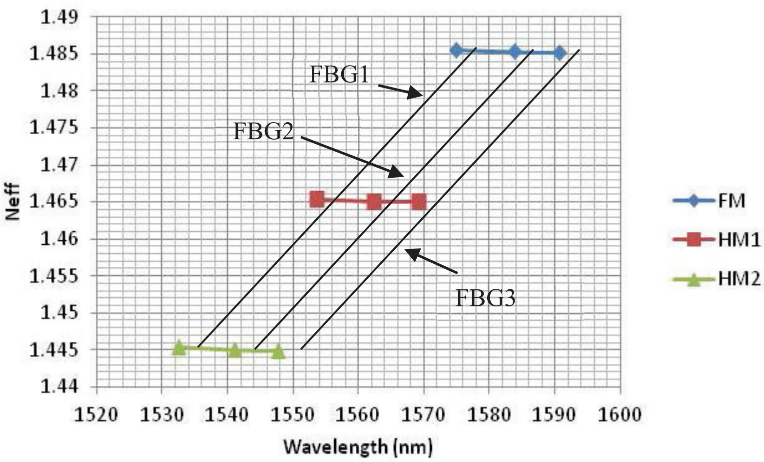


Fig. 3. Effective index of the modes existing in the few mode fiber FBG samples.

2.2 Inter-modal Interference Measurement

The mode interference pattern in the few-mode fiber inter-modal interferometer is used for effective refractive index difference analysis. The inter-modal interferometer consists of a piece of few mode fiber spliced between two pieces of single mode fibers (Fig. 4). The fundamental mode in the single mode fiber at the launching side will be split into multiple modes in the few-mode fiber by properly controlling the launching condition. The few modes propagate separately in the few-mode fiber. As a result of propagation constant difference, phase differences between these modes are accumulated in the few mode fiber. When the modes reach the single mode fiber at the output side, the modes interfere with each other.

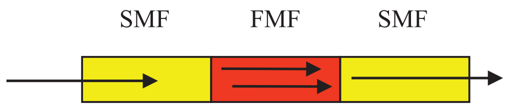


Fig. 4. The few-mode fiber inter-modal interferometer.

Assuming there are two modes (LP01 and LP11) existing in the few mode fiber, at a given wavelength, the two modes interfering in the second single mode fiber can be expressed as

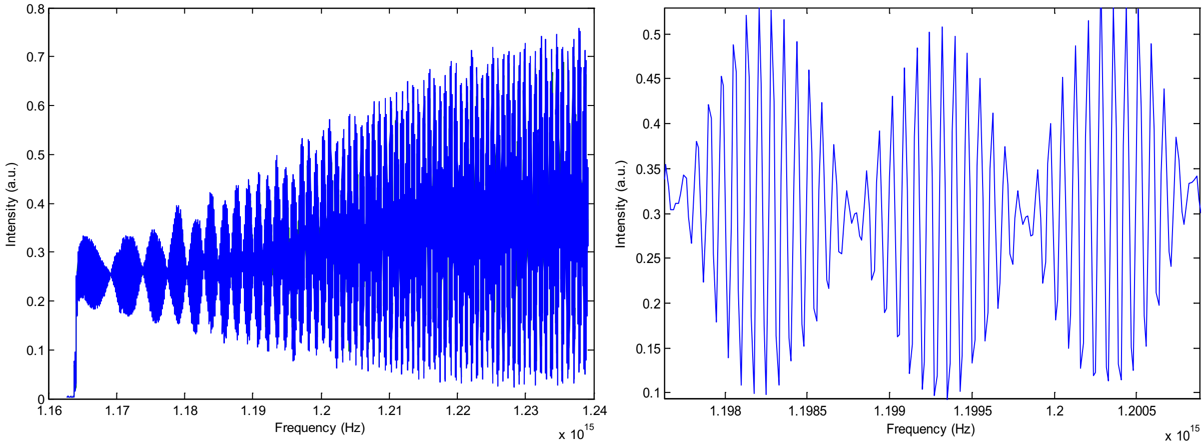
$$E = E_1 + E_2$$
$$= \sin(\omega t + 2\pi L * n_{eff1}/\lambda) + \sin(\omega t + 2\pi L * n_{eff2}/\lambda)$$
$$= 2\sin\left(\omega t + 2\pi L * \frac{n_{eff1}+n_{eff2}}{2\lambda}\right)\cos\left(2\pi L * \frac{n_{eff1}-n_{eff2}}{2\lambda}\right) \quad (1)$$

where E1 and E2 are the light waves from mode LP01 and LP11, respectively. ω is the angular frequency of the propagating wave, $\omega = 2\pi c/\lambda$. λ is the wavelength of the propagating wave. L is the physical length of few-mode fiber. n_{eff1} and n_{eff2} are the effect refractive indexes of the two guided modes LP01 and LP11, respectively. The intensity of the light after interference is

$$I \propto \cos(2\pi L * (n_{eff1} - n_{eff2})/\lambda). \quad (2)$$

When $(n_{eff1} - n_{eff2})$ is constant across the wavelengths, $(n_{eff1} - n_{eff2})$ can be calculated from the interference pattern, or from the inverse Fourier transform of the interference pattern. However, in real case, optical fibers have dispersions. Hence, $(n_{eff1} - n_{eff2})$ changes with the wavelengths, the calculation of $(n_{eff1} - n_{eff2})$ from the interference pattern will cause error, especially when the dispersions are large.

Figure 5 (a) shows the intensity across the angular frequencies (ω) of the light, after the light propagating through the interferometer configuration consisting of the few-mode fiber with a length of 0.5m, where $\omega = 2\pi c/\lambda$. The full wavelength range is from 1520 nm to 1620 nm. Figure 5 (b) shows enlarged graph of the interference in the range from 1570 nm to 1573 nm. A direct calculation of $(n_{eff1} - n_{eff2})$ from the time response of the interference pattern will result in about 0.05 difference between two adjacent modes. The 0.05 difference is almost larger than the difference between the core index and cladding index and is obviously wrong. The large error is caused by the dispersions of the fiber. The time response (Fig. 6) is inverse Fourier transform of the measured spectrum, which shows a wide spread indicating high order dispersions.



(a) (b)

Fig. 5. Measured optical modes interference in the few mode fiber sample.

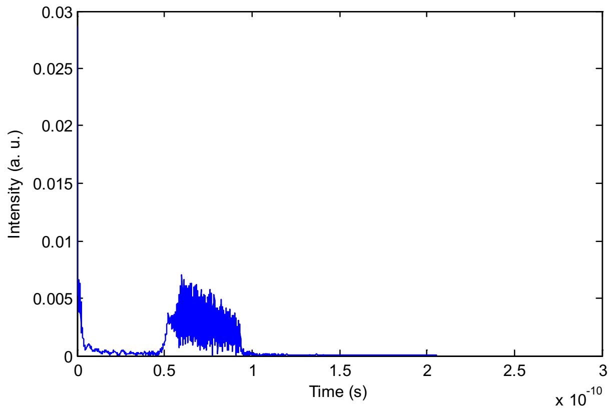


Fig. 6. Calculated time response from the measured optical modes interference in the few mode fiber.

2.3 Simulation on Inter-modal Interference

The simulation of inter-modal interference started with the three modes' refractive indexes obtained from the linear fitting of measured indexes (Fig. 7) from the three FBGs. Figure 8 (a) shows the interference spectrum in the wavelength range from 1520 nm to 1620 nm. The angular frequency is $\omega = 2\pi c/\lambda$. Figure 8 (b) shows enlarged graph of the interference in the range from 1570 nm to 1573 nm. Comparing Fig. 8 with Fig. 5, we found that the simulated interference has a similar pattern as the measured one. However, due to linear dispersion assumed in the simulation, the interference pattern is consistent across the wavelength or frequency, while the measured interference pattern changes its beating along the angular frequency. Figure 9 is inverse Fourier transform of the simulated interference spectrum, which shows the three narrow peaks corresponding to interference between fundamental mode, HM1, and HM2. Comparing Fig. 9 with Fig. 6, we found that the measured interference has much larger high order dispersions.

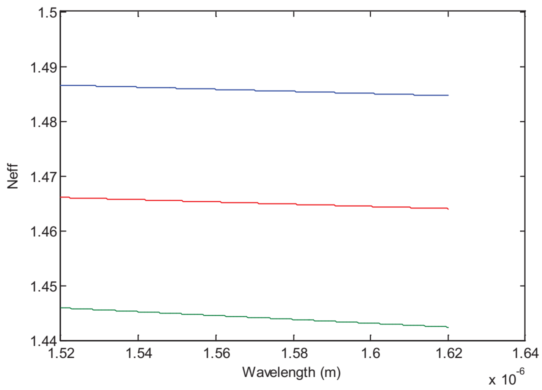


Fig. 7. Mode effective refractive indexes from the linear fitting of measured indexes from the three FBGs.

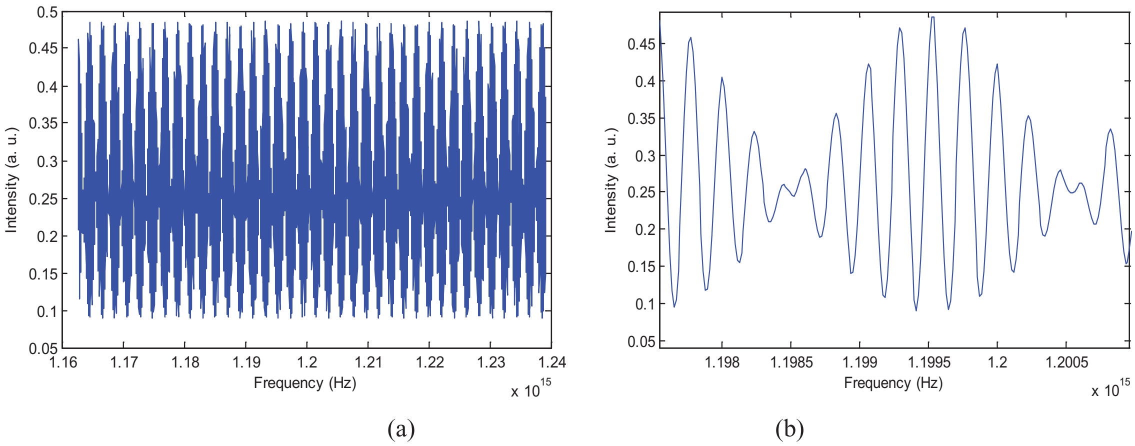


Fig. 8. Simulated optical modes interference in the few mode fiber by considering the linear dispersion in the few-mode fiber.

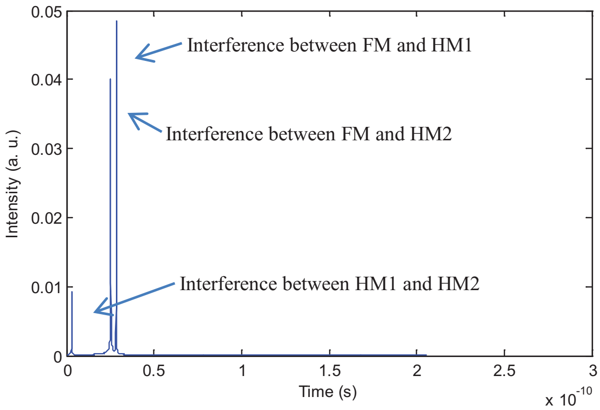


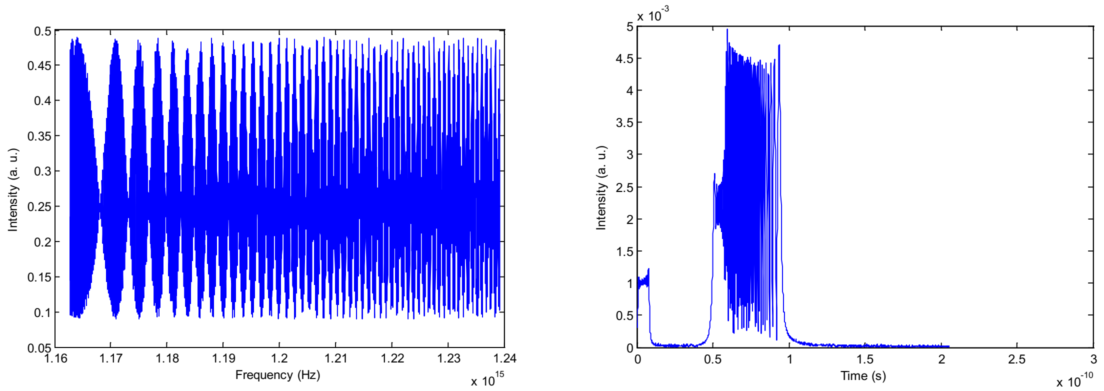
Fig. 9. Calculated time response from the simulated optical modes interference in the few mode fiber.

By introducing higher-order dispersions and adjusting total dispersions of the modes in the simulation, the simulated interference pattern and time response are optimized toward the simulated interference pattern and time response. By matching the simulated interference pattern and time response with the measured interference pattern and time response, more accurate modes effective refractive indexes are obtained for the few-mode fiber.

3. Result and Analysis

After adding the second-order dispersion component and adjusting total dispersions of the modes, and optimizing of the dispersion components, a new set of effective refractive indexes of the three modes across the wavelengths are obtained. With the new indexes, the simulated modes interference pattern and its time response are calculated and shown in Fig. 10. The trend of interference pattern change along with the frequency in Fig. 10 (a) is consistent with the trend in Fig. 5 (a). The time response in Fig. 10 (b) has a pattern close to that in Fig. 6. Better matching between the measured interference pattern and simulated interference pattern is achieved after the optimization process. Hence, the new effective refractive indexes of the three modes are more accurate than those directly calculated from FBGs or from interference pattern. Fig. 11 shows the effective refractive index differences between the fundamental mode and the high order modes, before and after the optimization. The dotted lines are from the linear extrapolation of the neffs from the three FBGs. The solid lines are obtained after optimizing the dispersion to match the interference pattern.

There are still slight mismatch between the measured pattern and simulated pattern which is caused by 3rd and even higher order dispersions of the modes in the fiber. By adding more higher order dispersion parameters in the optimization program, more accurate neff difference measurement will be achieved. Besides, there may be modes other than the simulated three modes existing in the few-mode fiber sample, which caused the slow envelope change in the measured pattern (Fig. 5). These modes are not captured in FBG measurement due to their too close vicinity to other modes.



(a) (b)

Fig. 10. Simulated optical modes interference in the few mode fiber after optimizing the dispersion for the few-mode fiber.

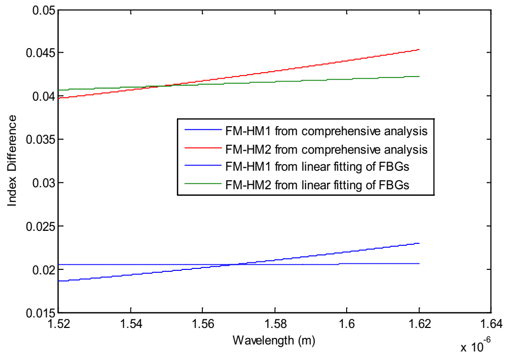


Fig. 11. The modes effective refractive index difference across the wavelengths.

4. Conclusions

In this study, we simulated the interference phenomenon between the modes in few-mode optical fiber. A comprehensive method is proposed which consists of analysing both FBGs and the interferometer to investigate the modes refractive index differences in few-mode fibers more accurately and for all the modes simultaneously. The proposed method proves to give a more accurate measurement result for few-mode fibers and better support the applications of few-mode optical fibers.

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