Wavelength Variation Approach in Single Mode-Multimode-Single Mode Optical Fiber as a Bending Sensor

Abdul Samee Khan, Prof. Mohd. Sarwar Raeen
All Saints’ College of Technology, Bhopal

Abstract

Multimode interference in optical waveguides has interesting self-imaging properties, which have extensively been investigated and utilized in many integrated optical devices. Multimode interference has also been explored in optical fibers in order to realize fiber devices, including sensors. A basic structure of these devices has been the Single mode – Multimode – Single mode (SMS) fiber section concatenation. This dissertation describes theoretical and numerical investigations on multimode interference (MMI) devices using a single mode-multimode-single mode (SMS) fiber structure for possible use as bending sensor using wavelength variation technique. Several aspects of the SMS edge filters have been investigated, including the effect of bending the SMS fiber cores due to fabrication tolerances, polarization dependence, and temperature dependence. These aspects can impair the performance of a wavelength measurement system. There are several approaches which have been proposed and demonstrated to achieve high resolution and accuracy of wavelength measurement. Bending effects due to the splicing process on the spectral characteristics of SMS fiber structure are investigated experimentally with the help of MATLAB. A limit for the tolerable of the cores of an SMS fiber structure based sensor is proposed, beyond which the fiber spectral performance degrades unacceptably. We use Wavelength variation approach by which we can measure the bending more accurately in optical waveguide, as compare to recent sensors. Due to the power loss the power transmission is decreases and efficiency also reduces. So by wavelength variation approach we developed an efficient spectrometer capable of performing a wide variety of coherent multidimensional measurements at optical wavelengths. In this approach we fixed the power and calculate the variation in the wavelength to sense the bending accurately. We apply our algorithm for performing several comparison considerations which shows the performance of our algorithm which is better in comparison to the previous work.

Keywords

Single mode Fiber, Multi-Mode Fiber, Power Loss, Bending

I. Introduction

The core aim of this research is to investigate all-fiber multimode interference (MMI) devices based on a graded index single mode-multimode-single mode (SMS) fiber structure for use as a new type of sensor for accurate and improved sensing of bending.

The research investigates bending sensor based on SMS fiber structures and introduces an approach which can sense the bending more accurately. After a deep observation and study of all the related research we observe that the bending sense in the optical fiber is not appropriate. The analysis is not better in the previous research, so the calculated efficiency is also not correct. So in proposed approach, author changes the method for sensing the bend in fiber. Uses an efficient wavelength variation approach for sensing the bending. So we can calculate the actual observation of the power loss and which is comparable.

Single mode multimode single mode (SMS) fiber structures have been investigated for use in several applications, e.g., as a refractometer, a band pass filter, and an edge filter [1][2][3][4]. An optical device based on the SMS fiber structure offers an all-fiber solution for optical communications and optical sensing applications with the advantages of simplicity of packaging and ease of interconnection to other optical fibers.

Multimode interference-based devices (MMI) are considered suitable candidates for this application. MMI devices are utilized in different optical processing applications. This is mainly due to their wide wavelength band, ease of fabrication and integration, and fabrication tolerance. MMI devices have been utilized as optical power splitters, combiners, optical hybrid couplers, multiplexers, and demultiplexers [5][6][7][8][9].

Several aspects of the SMS edge filters have been investigated, including the effect of misalignment the SMS fibre cores due to fabrication tolerances, polarization dependence, and temperature dependence. These aspects can impair the performance of a ratiometric wavelength
measurement system. Several approaches have been proposed and demonstrated to achieve high resolution and accuracy of wavelength measurement. Misalignment effects due to the splicing process on the spectral characteristics and PDL of SMS fibre structure-based edge filters are investigated numerically and experimentally. A limit for the tolerable misalignment of the cores of an SMS fibre structure-based edge filter is proposed, beyond which the edge filter’s spectral performance degrades unacceptably. In this paper we analyse several aspects and then apply our algorithm for overcome the problems.

The remaining of this paper is organized as follows. We discuss MMI in optical fiber Section 2. In Section 3 we discuss about beam propagation analysis. The Evolution and recent scenario in section 4. In section 5 we discuss about proposed approach. The conclusions and future directions are given in Section 6. Finally references are given.

II. MMI in Optical Fiber

MMI is a useful basis for the implementation of a number of optical waveguide devices. MMI was investigated and proposed at first for planar waveguides. MMI based devices implemented in planar waveguides have been developed for optical signal processing applications and for optical sensing applications.

A useful basis for visualizing and gaining a better understanding of MMI in a multimode waveguide is the phenomenon of self-imaging. Self-imaging can be defined as a property of multimode waveguides by which an input field profile is reproduced due to constructive interference to form single or multiple images of the single mode input field at periodic intervals along the propagation direction.

In an optical fiber, MMI can be implemented using a fiber hetero-structure consisting of a single mode-multimode-single mode (SMS) fiber structure with a step index profile. An SMS fiber structure can be fabricated by splicing a precisely dimensioned multimode fiber (MMF) section between two singlemode fibers (SMFs). Figure 1 shows a schematic diagram of an SMS fiber structure. SMS fiber structures can utilize either a step index or a graded index profile MMF. SMS structures using a graded index profile MMF section have been demonstrated by several authors where the effects of beam interference were investigated and micro bend, strain, and temperature sensors were demonstrated.

Figure 1: Wavelength Variations in SMS Optical Fiber Structure

The general requirements for an ideal discriminator in a wavelength measurement system are as follows: 1) high resolution (better than 10 pm) and high accuracy, 2) high measurement speed to allow measurement of dynamic strain and 3) cost effectiveness. In addition a wide wavelength range (> 10 nm) is needed where wavelength division multiplexed FBGs are used.

III. Multimode Fiber Dimensions

The core aim of this research is to investigate all-fiber multimode interference (MMI) devices based on a graded index single mode-multimode-single mode (SMS) fiber structure for use as: 1) a new type of edge filter for a ratio metric wavelength measurement system and as (2) sensors for bending sense. The MMF section can support many guided modes and the input field is reproduced as single image at periodic intervals along the propagation direction due to the interference between these guided modes. This is the so-called self-imaging principle and the distance at which self-imaging occurs is called the reimaging distance. The approach used here to analyze the field distribution in the MMF section is a beam propagation analysis.

To design the SMS-based edge filter, the MMF length needs to be determined. It has been shown that the re-imaging distance is wavelength dependent. If re-coupling into the output SMF takes place at the reimaging distance, then the MMF section of the SMS structure has by definition a length equal to the re-coupling distance and operates as a band pass filter. However, for the purpose of designing an edge filter, the band pass response can be considered as two spectral responses, on the either side of a center wave length. Consequently, the device can behave as an edge filter for a selected wavelength range. Two SMS-based edge filters with opposite slope spectral responses within a given wavelength range can be obtained by choosing two band pass filters with appropriate center wavelengths.

Multimode fiber optic cable has a large diametral core that allows multiple modes of light to propagate. Because of this, the number of light reflections created as the light passes...
through the core increases, creating the ability for more data to pass through at a given time. Because of the high dispersion and attenuation rate with this type of fiber, the quality of the signal is reduced over long distances. This application is typically used for short distance, data and audio/video applications in LANs. RF broadband signals, such as what cable companies commonly use, cannot be transmitted over multimode fiber.

Figure 2 shows the Multimode dimensions. Multimode fiber is usually 50/125 and 62.5/125 in construction. This means that the core to cladding diameter ratio is 50 microns to 125 microns and 62.5 microns to 125 microns.

Figure 2: Multimode Construction

**Graded-Index Multimode Fiber** - Contains a core in which the refractive index diminishes gradually from the center axis out toward the cladding. The higher refractive index at the center makes the light rays moving down the axis advance more slowly than those near the cladding. Due to the graded index, light in the core curves helically rather than zigzag off the cladding, reducing its travel distance. The shortened path and the higher speed allow light at the periphery to arrive at a receiver at about the same time as the slow but straight rays in the core axis. The result: digital pulse suffers less dispersion. This type of fiber is best suited for local-area networks.

**IV. Evolution and Recent Scenario**

In 2008, Qian Wang et al. [11] present an investigation on a single mode multimode–single-mode fiber structure. A one-way guided-mode propagation analysis for the circular symmetry waveguide is employed to model the light propagation and the approximated formulations are derived and evaluated concerning the accuracy. Phase conjugation of the multimode interference within the fiber structure is revealed. A simple way to predict and analyze the spectral response of the structure is presented through the space to wavelength mapping with the derived approximated formulations. The prediction of spectral response is verified numerically and experimentally.

In 2009, Agus Muhamad Hatta et al. [13] study about Misalignment effects on the spectral characteristics of edge filters based on single mode–multimode–singlemode (SMS) fibre structures are investigated numerically and experimentally. A beam propagation analysis is used with a set of guided modes calculated using the finite-difference method to determine the transmission loss of the SMS-based edge filters. A limit for the tolerable misalignment of the SMS fiber-based edge filter is proposed, beyond which the spectral performance of the SMS structure degrades unacceptably. The numerical results are verified experimentally with good agreement.

In 2011, Ahmed Hisham Morshed et al. [14] reports multimode interference in optical waveguides has interesting self-imaging properties, which have extensively been investigated and utilized in many integrated optical devices. Although these investigations started with most interest in step index integrated waveguides, they have later included graded index waveguides, where the dependence of the interference images on the refractive index grading of the waveguides was observed and utilized in the design and optimization of devices. Later on, multimode interference has also been explored in optical fibers in order to realize fiber devices, including sensors. A basic structure of these devices has been the Single mode Multimode Single mode (SMS) fiber section concatenation, where multimode interference in the multimode section leads to the formation of a self-image of the single mode fiber excitation onto the output single mode fiber core.

**V. Proposed Approach**

Self-imaging in symmetrically excited multimode optical fibers is analytically studied to explore the effects of refractive index grading on SMS fiber device characteristics. The Beam Propagation Method (BPM) is used to simulate optical field propagation in multimode fibers with different index grading distributions to verify the analytically obtained results. Preliminary experimental investigations of an SMS structure intended to be a bending sensor are used for sense the bend.

After a deep observation and study of all the related research we observe that the bending sense in the optical fiber is not appropriate. The analysis is not better in the previous research, so the calculated efficiency is also not correct. Due to the bending the power transmission losses are increases and efficiency reduces. So by wavelength variation approach we developed an efficient spectrometer capable of performing a wide variety of coherent multidimensional measurements at optical wavelengths. In this approach we fixed the power and perform variation in the wavelength to sense the bending accurately.

Self-imaging in symmetrically excited multimode optical fibers is analytically studied to explore the effects of refractive index grading on SMS fiber device characteristics. The
operation of the SMS structure explored here as a bending sensor by monitoring the optical power transmitted through the structure under static bending was difficult to achieve due to the fast beating spectral transmission peaks.

The power transmission spectra of the device under different bending conditions were measured and its operation as a bending sensor was investigated. The transmitted power spectra of the structure were measured without the structure; its transmission spectra were extracted and normalized to the maximum transmission value. So in our approach we consider the power as the constant factor and wavelength as a variable to sense more bending in comparison to the previous study.

In our proposed approach we select a wavelength between 1350nm to 1700nm for signal transmission. When the signal is propagated from the, when the bending will occur in the optical fiber it causes the change in the refractive index of the core of multimode fiber. This change in the refractive index introduces a shift in the wavelength of the signal which is transmitted through this bent fiber. Higher the value of wavelength shift shows the large radius bending in the fiber.

Wavelength Sensitivity of the SMS Structure

The coupling loss of the SMS fiber structure depends strongly on the length of the MMF as shown in Fig. 3, but it is also wavelength sensitive. The approximated can be rewritten as below through substituting

\[ L_z = \frac{16n_o a^2}{\lambda} \]  
\[ \ldots \ldots \ldots \ldots (4.1) \]

\[ L_z(\lambda, z) = 10 \log_{10} \sqrt{\sum_{m=1}^{M} c_m^2 \exp \left( -i \left( (2m + 1)(2m - 1) \pi \right) \right)} \]  
\[ \ldots \ldots \ldots \ldots (4.2) \]

\[ g(\lambda, Z) = \lambda z / 16n_o a^2 \]  
\[ \ldots \ldots \ldots \ldots (4.3) \]

Neglecting the wavelength dependence of the excitation coefficient \( c_m \) and the material dispersion of the fiber core \( n_o \) (the numerical examples below indicate that this is reasonable), we can see that the transmission of the fiber structure with a wavelength shift equals to that with a length variation of MMF, i.e

\[ L_z(\lambda, z_0) = L_z(\lambda_o, z_0 + \Delta z) \]  
\[ \ldots \ldots \ldots \ldots (4.4) \]

Only if

\[ \Delta \lambda / \lambda_o = \Delta z / z_o \]  
\[ \ldots \ldots \ldots \ldots (4.5) \]

For a given length of MMF, the peak wavelength of the band pass filter can be found by simulating light propagation using

the Beam propagation analysis presented in Section II-A. Alternatively, it can also be determined based on [14] with a good accuracy. For the SMS fiber structure with a length \( L_0 \) of the MMF, the corresponding peak wavelength of the band pass filter is assumed to be \( \lambda_0 \). When the length of multimode fiber is change to be \( L_1=L+\Delta L \), the peak of wavelength \( \Delta \lambda \) can be calculated approximately according to [14], i.e.

\[ L_0 (\lambda_o, L_0) = L_1 (\lambda_o+\Delta \lambda, L_0+\Delta L) \]  
\[ \ldots \ldots \ldots \ldots (4.6) \]

This leads to

\[ \Delta \lambda = - (\Delta L / L_0) \lambda_o \]  
\[ \ldots \ldots \ldots \ldots (4.7) \]

Similarly

When the refractive index of multimode fiber is to be change \( N_1=N_0+\Delta N \), the shift of peak wavelength \( \Delta \lambda \) can be calculated by:

\[ \Delta \lambda = - (\Delta N / N_0) \lambda_o \]  
\[ \ldots \ldots \ldots \ldots (4.8) \]

So by using equation 4.8 , shift in the operating wavelength \( \Delta \lambda \) due to change in refractive index, is calculated.

Flow chart for methodology, figure 4.3
VI. Result Evaluation

The result for bend sensing in multimode fibers is shown in Figure 4.4 and 4.5. 3 cm and 10 cm bending is taken or considered from both the values which is lower and the higher. The effect of bending on the spectral response of an SMS-based sensor has been investigated. An MPA with a calculated set of guided modes using beam propagation is employed to analyze the misalignment effect. It is shown that the performance of the SMS-based optical fiber degrades when the lateral misalignment is larger than a misalignment limit equal to the core radius of the SMF used.

By observing the wavelength variation during the transmission, we found, when the radius of bending in fiber is increases then the relative power transmission is affected and the shift in the wavelength is increases as the bending is increases. So by comparing the received power at different wavelength and measuring the shift in wavelength, receiver can observe that signal is distorted due to bending. And can improve the efficiency by removing these bend if possible. This research investigation improves the bend sensing in optical fiber which was very difficult in previous researches.

The transmitted power spectra of the structure were measured using a broadband source and an optical spectrum analyzer and using the power spectrum measured without the structure, its transmission spectra were extracted and normalized to the maximum transmission value. The transmission spectrum obtained with bending is shown in Figure 4.4. In this we put the power part as a constant factor and the wavelength part as the variable part.

VII. Conclusion and Future Directions

Multimode interference in optical waveguides has interesting self-imaging properties, which have extensively been investigated and utilized in many integrated optical devices. Although these investigations started with most interest in step index integrated waveguides, beam propagation they have later included graded index waveguides, where the dependence of the interference images on the refractive index grading of the waveguides was observed and utilized in the design and optimization of devices. But there are several drawbacks including the weak sensing of bend and one sided interference is possible. So we adopt beam propagation with constant power method with two way sensing mechanism which is better adaptation in bend sensing.

References


Mohd. Sarwar Raeen Received the B.E. in Electronics and Communication Engineering From RGPV Bhopal and M.Tech. In Digital Communication From MANIT Bhopal, India, in 2003 and 2008 Respectively. He is currently an Associate Professor With the Department Of Electronics and Communications Engineering in All Saints’ College of Technology Bhopal, India. From June 2008 to Till Date, His Professional Research Interests Involve VLSI In Communication And Optical Communication.

Abdul samee Khan received the B.E. degree In Electronics and Communication Engineering from Rajiv Gandhi Ptdoyogiki Vishwavidyalaya, Bhopal, M.P. India in 2009. Presently he is pursuing here M.Tech. Degree in Digital Communication engineering from Rajiv Gandhi Ptdoyogiki Vishwavidyalaya, Bhopal, M.P. India.