New Design of Optical Filters Based on Single Mode-Multimode-Single Mode Fiber Structure for Optical Fiber Communication Systems

Jassim Kadim Hmood*
Received on: 18/7/2011
Accepted on: 6/10/2011

Abstract
In this paper, a design of optical filters based on single mode-multimode-single mode fiber structure (SMS) is demonstrated. The multimode interference effect can be utilized to design wavelength-selective devices with high extinction ratio. The proposed optical filters are realized by using standard optical fibers.

Two optical filters are designed to operate with wave division multiplexing (WDM) communication system in two channels at wavelength of 1310 nm and 1550 nm. First filter has power transmission of -0.253/-35 dBm at wavelengths of 1310/1550 nm respectively, while, second one has power transmission of -32/-1.35 dBm at wavelengths of 1310/1550 nm respectively. In addition, power transmission curves, spectral response curves, and propagation field of SMS structure in two and three dimensions are plotted.

Keywords: Optical filters, Multimode interference, self-imaging, single mode – multimode – single mode structures and WDM-PON.

1. Introduction

The enormous potential of WDM technology is widely used in today's telecommunication networks. However, the economical factor makes WDM systems available only for application in long-haul systems with demand for high capacity (the order of Tbit/s) [1]. In WDM transmission systems, wavelength multiplexers / demultiplexers play essential roles in combining / separating information carried by different wavelengths. Of particular interests to optical telecommunications are the 1310 nm and 1550 nm windows. In fiber-to-the-home...
(FTTH) services, these two windows are used to carry data / voice and video, respectively [2]. Using such a system telecom operators would be able to multiplex various technologies / services via one fiber, for example, Ethernet for data services and a single mode-multimode-single mode (SMS) fiber structure is a combination of two different types of optical fiber, where a short length of multimode fiber (MMF) is sandwiched between input and output single mode fibers (SMFs). The light injected from the input SMF excites multiple modes propagating in the MMF. Interference occurs between these modes (multimode interference) and as a result, the nature of the light reaching the output SMF is dependent on a number of physical parameters, such as refractive index, core diameter and the length of the MMF section. This dependence gives SMS fiber structures great potential STM-4 for telephony applications, or multiplex several physical (e.g. Ethernet) links for the purpose of greater capacity and / or reliability [3]. For use as sensors or other components, such as optical filters in optical Multimode interference (MMI) in multimode waveguides has interesting self-imaging properties, which have extensively investigated and utilized in many integrated optical devices. The MMI effect can be utilized to design wavelength-selective devices with high extinction ratio or This paper presents a new type of optical filter based on an SMS fiber structure 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 of the guide. In SMS fibers structure, where multi mode 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 [9] used to obtain simulation results. One SMS fiber structure is optimized to provide optical filters spectral response for WDM communication system, and introduces this optical filter into optical fiber communication system (e.g. WDM-PON). Self-imaging in symmetrical excited multimode optical fibers is simulated to explore the effects of MMF length on SMS fiber device characteristics. To simulate optical field propagation in SMS fiber structures, the beam propagation method (BPM) used to obtain simulation results. One SMS fiber structure is optimized to provide optical filters active controllable devices by refractive index modulation [8]. Self-imaging can be defined as a property of multimode waveguides by

and excites all the modes supported by the MMF. Single images of the SMF input signal will appear along the MMF at periodic

The coupling loss of the SMS fiber structure depends strongly on the length of the MMF but it is also wavelength sensitive. Corresponding
New Design of Optical Filters Based on Single Mode-Multimode-Single Mode Fiber Structure for Optical Fiber Communication Systems

Accordingly, with the approximation of propagation constants, the transmission of SMS fiber structure can be calculated by [9]:

\[ L_e(z) = 10 \log_{10} \left( \sum_{m=0}^{\infty} c_m^2 \exp\left(-i\frac{(2m+1)}{L_e(z)}z\right) \right) \]  \hspace{1cm} (1)

Where, \( c_m \) is the excitation coefficient of each mode and \( M \) is excited mode number of the multimode fiber. It can be calculated by:

\[ M = \frac{V}{\pi} \] \hspace{1cm} (2)

And,

\[ V = \frac{2\pi \cdot d \sqrt{n_{co}^2 - n_{cl}^2}}{(2m-1)\pi} \frac{\lambda}{g(\lambda, z)} \] \hspace{1cm} (3)

where \( g(\lambda, z) = \frac{\lambda z}{16 n_{co} a^2} \), and;

\[ c_m = \frac{\int E_r(r, 0) F_m(r) \, rdr}{\int F_m(r) F_m(r) \, rdr} \] \hspace{1cm} (5)

where \( E_r(r, 0) \) is the input light to the multimode fiber and \( F_m \) is the field profile of \( LP_{0m} \). In other words, due to the circular symmetric characteristic of fundamental mode of the single-mode fiber, the input light is assumed to have a field distribution of \( E(r, 0) \). When the light launches the multimode fiber, the input field can be decomposed by the eigenmodes of \( \{LP_{n,m}\} \) the multimode fiber. Due to the circular symmetric of input field and an ideal alignment assumed above, only the \( LP_{0,n} \) modes can be excited [9].

According to MMI theory, the peak wavelength of a MMI device is given by [5]:

\[ \lambda_p = 4p \frac{n_{co} \cdot a^2}{L} \] \hspace{1cm} with \( p = 0, 1, 2, \ldots \) (6)

Where, \( V \) is the normalized frequency, \( a \) is the radius of the multimode fiber core, \( n_{co} \) is refractive index of multimode fiber core and \( n_{cl} \) is refractive index of multimode fiber cladding and \( \lambda \) is the wavelength of light in the free-space.

\[ 1 - \frac{16 n_{co} a^2}{\lambda} \]  \hspace{1cm} By substituting in the approximation (1) can be re-written as below:

\[ L_e(z) = 10 \log_{10} \left( \sum_{m=0}^{M} c_m^2 \exp(-i(2m+1)) \right) \]

where \( L \) is the length of the MMF and \( p \) is the self-image number. As shown in Eq. (6), the peak wavelength response of the MMI filter can be selected by simply changing the length of the MMF. An additional advantage when changing the length of the MMF for optimizes the optical bandwidth of filter, a linear wavelength response of the MMI device is obtained.

3. Simulation Results

As an example to illustrate the design process, an optical filter with wavelength range for WDM-PON network from 1310 to 1550 nm was chosen. This range was chosen as it corresponds to the typical centre wavelengths for two wavelength passive optical network [10]. The SMS structure formed from standard silica optical fibers. The standard single mode fiber (SMF-28) is chosen as the single-mode fiber section, of which the parameters are: the refractive in-
The propagating fields of first filter (length of MMF is 13.8 mm) at wavelengths of 1310 nm and 1550 nm is shown in Fig.(2). It is clear that (in MMF section) self-imaging of the input field takes place so that at periodic intervals, a single image of the input field is reproduced. This occurs at distance of 4442 µm and 8884 µm from starting of MMF section at wavelength of 1310 nm and lower transmission at wavelength of 1550 nm. Also, optimizing MMF length L=11.65 mm in order to achieve the best transmission power at wavelength 1310 nm and lower transmission at wavelength of 1550 nm. The propagating fields of second filter (length of MMF is 11.65 mm) at wavelengths of 1310 nm and 1550 nm is illustrated in Fig. (5). It can be seen that the field amplitude at output of SMS structure is high at 1550 nm as shown in Fig.(5-b). While the amplitude of field is very low and field will lost in the cladding. The power transmission of an SMS structure with multimode fiber length of 11.65 mm is illustrated in Fig.(6). From Fig.(6), it can be note that the transmission of
SMS structure with MMF length of 11.65 mm is 73.2% at wavelength of 1550 nm and 0.0627% at wavelength of 1310 nm. Fig.(7) shows the optical power spectrum as a function of wavelength from 1250 to 1610 nm. At wavelength of 1550 nm, the output power in the outputs of SMS structure is equal to -1.35 dBm. There is about 27% energy loss during the propagation. At wavelength of 1310 nm, the output power of SMS structure is equal to -32 dBm. In fact, the spectral response of proposed filter is not flat and has a band-pass type response, where the band-pass peak wavelength corresponds to the wavelength value where the self-imaging distance is exactly equal to the multimode section length. In other words, it can provide an optical filter response with a reasonable discrimination range. These features of proposed optical filters make it use optical fiber communication systems especially in wave division multiplexing - passive optical networks (WDM-PON) operate with two wavelengths (1310 nm and 1550 nm).

5. Conclusions

In conclusion, a simple optical fiber filter based on the MMI phenomenon of self-imaging was investigated. The MMI effect can be utilized to design wavelength -selective devices with high extinction ratio. The optical filter was utilized composed of single mode - multimode - single mode fiber structure. The optical filters were realized by using standard optical fibers. The transmission spectrum of the two different optical filters at 1310 nm and 1550 nm were plotted, from which the device was found to be suitable for optical fiber communication system. First one has power transmission of -0.245 / -35 dBm at wavelengths of 1310 / 1550 nm respectively and second one has power transmission of -42 / -1.55 dBm at wavelengths of 1310 / 1550 nm. Additionally, the device is quite simple and relatively inexpensive when compared with other optical filters techniques.

References


Table 1: Properties of first optical filter with MMF length of 13.8 mm.

<table>
<thead>
<tr>
<th>MMF length(μm)</th>
<th>L_{MMF} = 13800μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1550nm</td>
</tr>
<tr>
<td>Transmission (%)</td>
<td>0.0315%</td>
</tr>
<tr>
<td>Output power (dBm)</td>
<td>-35dBm</td>
</tr>
<tr>
<td>Extinction ratio (dB)</td>
<td>35dB</td>
</tr>
</tbody>
</table>

Table 2: Properties of first optical filter with MMF length of 11.65 mm.

<table>
<thead>
<tr>
<th>MMF length(μm)</th>
<th>L_{MMF} = 11650μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1310 nm</td>
</tr>
<tr>
<td>Transmission (%)</td>
<td>0.0627%</td>
</tr>
<tr>
<td>Output power (dBm)</td>
<td>-32 dBm</td>
</tr>
<tr>
<td>Extinction ratio (dB)</td>
<td>32 dB</td>
</tr>
</tbody>
</table>

Figure (1): Schematic configuration of the single-mode–multimode–single-mode fiber structure.
Figure (2): The propagating fields of first filter (length of MMF is 13.9 mm) at wavelengths of 1310 nm and 1550 nm. (a) & (c) Propagating fields at 1310 nm in two & three dimensions respectively, (b) & (d) Propagating fields at 1550 nm in two & three dimensions respectively.
Figure (3): represent the transmission power through the SMS structure with MMF length of 13.8 mm.
   a) at wavelength of 1310 nm
   b) at wavelength of 1550 nm.
Table 1: Properties of first optical filter with MMF length of 13.8 mm.

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Transmission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.23</td>
<td>-50</td>
</tr>
<tr>
<td>1.31</td>
<td>-40</td>
</tr>
<tr>
<td>1.39</td>
<td>-30</td>
</tr>
<tr>
<td>1.47</td>
<td>-20</td>
</tr>
<tr>
<td>1.55</td>
<td>-10</td>
</tr>
</tbody>
</table>

Figure (4): Represent the transmission and output power spectrums of optical filter with MMF length of 13.8 mm.

a) Transmission versus wavelength
b) Output power versus wavelength
Figure (5): The propagating fields of first filter (length of MMF is 11.65 mm) at wavelengths of 1310 nm and 1550 nm. (a) & (c) Propagating fields at 1310 nm in two & three dimensions respectively, (b) & (d) Propagating fields at 1550 nm in two & three dimensions respectively.
Figure (6): represent the transmission power through the SMS structure with MMF length of 11.65 mm.

a) at wavelength of 1310 nm
b) at wavelength of 1550 nm.
Figure (7): represent the transmission and output power spectrums of optical filter with MMF length of 11.65 mm.

a) Transmission versus wavelength
b) Output power versus wavelength