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

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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.

تصميم جديد للمرشحات بصرية مرتكز على تركيب ألياف أحادي النمط - متعدد الأنماط -أحادي النمط للاتصالات الألياف البصرية

الخلاصة

في هذا البحث تم وصف تصميم مرشحات بصرية مرتكز على تركيب ألياف أحادي النمط-متعدد الأنماط-أحادي النمط. يمكن الانتفاع من تأثير التداخل متعدد الأنماط لغرض تصميم أجهزة تعمل على انتقاء الطول ألموجي مع نسبة إخماد عالية. المرشح البصري المقترح انتفع من استخدام الألياف البصرية المعيارية.

تم تصميم مرشحين بصريين ليعملا في منظومة اتصالات خلط تقاسيم الأطوال الموجية (WDM)في القناتين ذات الطولين الموجيين 1310 نانومتر و 1550 نانومتر. المُرشح (الفلتر) الأول له نفاذية مساوية إلى -0,253/ -35 dBm عند الطولين الموجيين 1310 / 1550 نانومتر على التوالي بينما المرشح الثاني فله نفاذية مساوية -32/-1,35 dBm عند الطولين الموجيين 1310 / 1550 نانومتر على التوالي . بالإضافة إلى ذلك, تم رسم كل من منحنيات النفاذية و منحنيات الاستجابة الطيفية وانتشار المجال داخل التركيب بصورتيه ثنائية وثلاثية الإبعاد.

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

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(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 andA 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, whichhave extensively investigated and utilized in many integrated optical devices. The MMI effect can be utilized to

2. Wavelength Sensitivity of the SMS Structure

The present optical filter consists of a multimode fiber placed between two single mode fibers as shown in

intervals along its axis, due to the interference between the modes as they propagate along the MMF [4, 5]

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 provideoptical filters spectral re sponse for WDM communication system. and introduces this optical filter into optical fiber communication system (e.g. WDM - PON). Self - imaging in symmetrically 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 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 periodical

The coupling loss of the SMS fiber structure depends strongly on the length of the MMF but it is also wavelength sensitive. Correspondingly, with the approximation of propagation constants, the transmission of SMS fiber structure can be calculated by [9]:

$$L_s(z) = 10\log_{10}\left(\left|\sum_{m=1}^{M} c_m^2 \exp\left(-i\left(\frac{(2m+1)(2m-1)p}{\overline{L}_z}\right)z\right|^2\right)\right) \qquad (1)$$

Where, c_m is the excitation coefficient of each mode and M is excited mode number of the multimode fiber. It can calculate by:

$$M = V/p \qquad (2)$$

And,

$$V = \frac{2p \cdot a\sqrt{n_{co}^2 - n_{cl}^2}}{l} \qquad (3)$$

$$(2m-1)p)g(l,z)|^2\Big) \qquad (4)$$

where $g(l,z)= lz/16\, n_{co}\, a^2$, and;

$$c_m = \frac{\int_0^\infty E(r,0)F_m(r)rdr}{\int_0^\infty F_m(r)F_m(r)rdr} \qquad (5)$$

where E(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 $LP_{0,m}$ modes can be excited [9].

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

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 λ is the wavelength of light in the free-space. By $\overline{L}_z = \frac{16\, n_{co}\, a^2}{l}$ substituting in the approximation (1) can be rewritten as below:

$$L_s(z) = 10\log_{10}\left(\left|\sum_{m=1}^{M} c_m^2 \exp(-i(2m+1)\right.\right.$$

$$l_o = 4p\frac{n_{co} \cdot a^2}{L} \quad \text{with} \quad p = 0,1,2,\ldots(6)$$

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 band 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 index for the core and cladding is 1.4504 and 1.4447, respectively, at wavelength 1550 nm and 8.3/125 μm core/cladding diameters [9]. The standard step-index multimode fiber has a 62.5/125 μm core/cladding diameters with refractive index of core/cladding are 1.491/1.4654 at 1300 nm [11].

The simulation is done by using BMP software to numerically simulate optical field propagation in different SMS fiber structures. In the simulation, the optimization of optical filter response is done by changing the length of the MMF. According to the simulation results, the MMF length is further optimized to L = 13.8 mm in order to achieve the best transmission power at wavelength 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 1550 nm and lower transmission at wavelength of 1310 nm. 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 as shown in Fig.(2-c). Multi-fold images of the input field can also be found, for example, fold images can be found at 2300, and 8970 μm. It can be seen from Fig.(3-c,d), The self-imaging occurs at specific lengths only for certain wavelengths.

Fig.(3) represent the transmission power through the SMS structure for first optical filter (length of MMF is 13.8 mm) at wavelengths of 1310 nm and 1550 nm. From Fig.(3), it can be note that the transmission of SMS structure with MMF length of 13.8 mm is 94.5% at wavelength of 1310 nm and 0.0315 % at wavelength of 1550 nm.

Fig.(4) shows the optical filter spectra response as a function of wavelength from 1250 to 1610 nm. At wavelength of 1550 nm, the output power of SMS structure is equal to -35 dBm. At wavelength of 1310 nm, the output power of SMS structure is equal to (-0.245 dBm). There is about 5.5% of energy loss during propagation. If the length of the multimode fiber changes a little from 13.8 mm to 13.86 mm, corresponding optical power spectrums will be a little left shift (dashed lines). It can be seen that the power at the output increased a little from -0.245 to -0.027 dBm at 1310 nm, while; the power at the output increased from -35 dBm to -25.5 dBm at 1550 nm. That is the reason why the length of the multimode fiber is chosen equal to 13.8 mm rather than L=13.86 mm for proposed optical filter.

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 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.

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

MMF length(μm)	L_{MMF}= 13800μm	
Wavelength (nm)	1550nm	1310nm
Transmission (%)	0.0315%	94.5%
Output power (dBm)	-35dBm	-0.245dBm
Extinction ratio (dB)	35dB	0.245dB

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

MMF length(μm)	L_{MMF} = 11650μm	
Wavelength (nm)	1310 nm	1550 nm
Transmission (%)	0.0627%	73.2%
Output power (dBm)	-32 dBm	-1.35 dBm
Extinction ratio (dB)	32 dB	1.35 dB

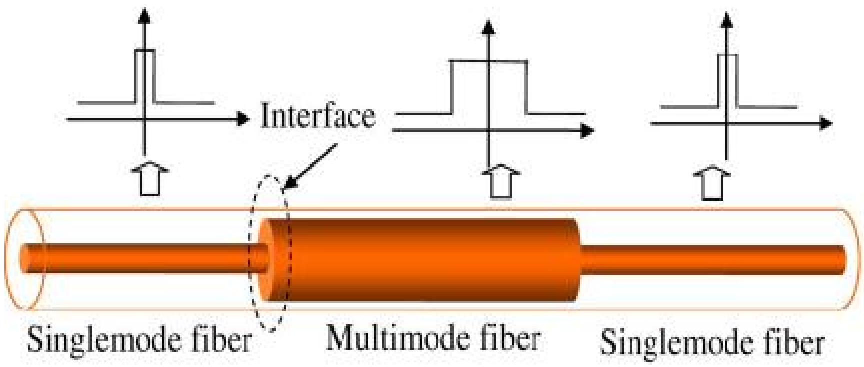
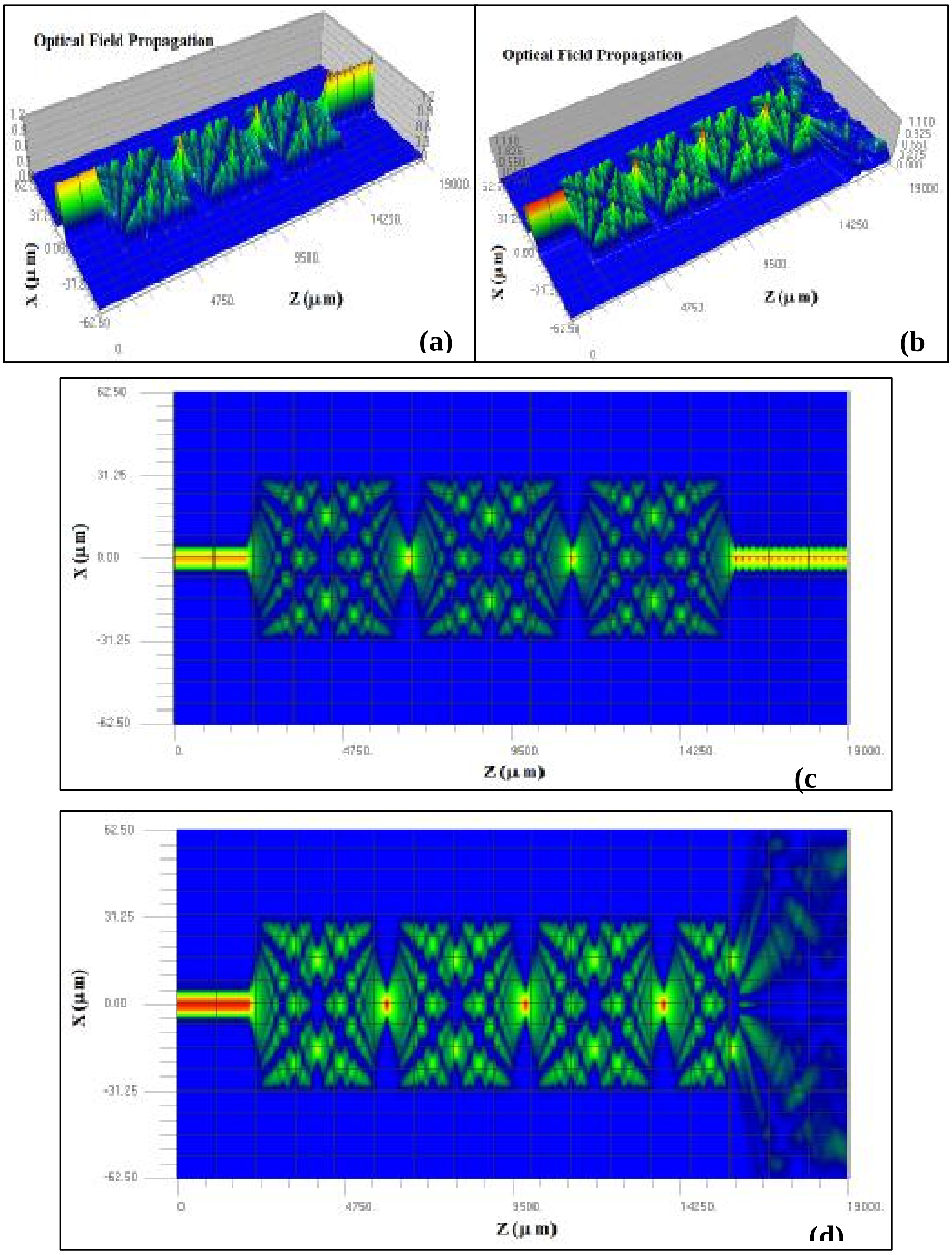
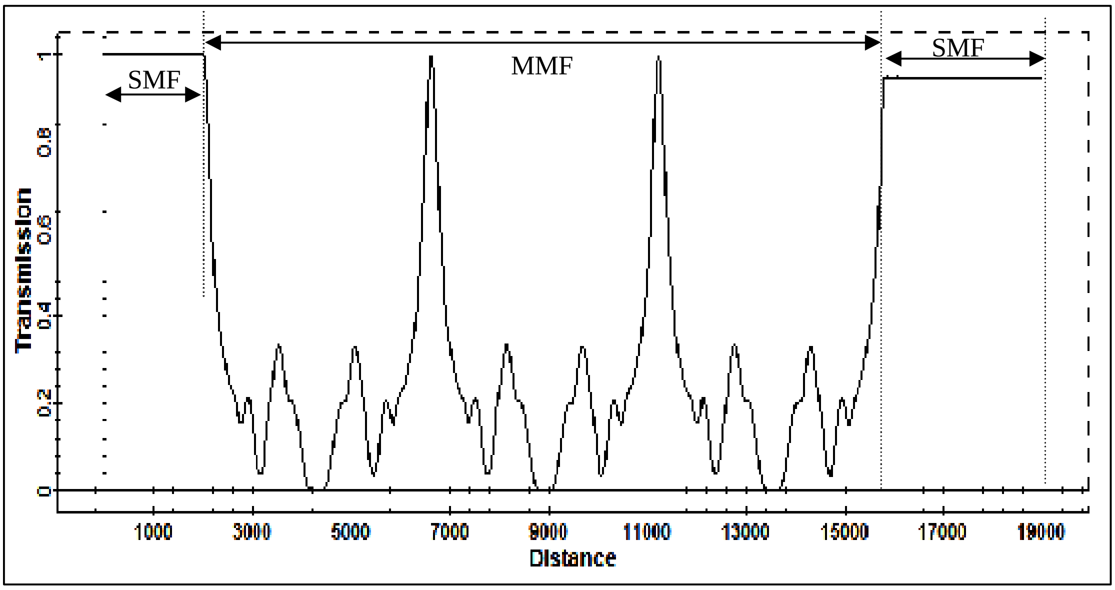


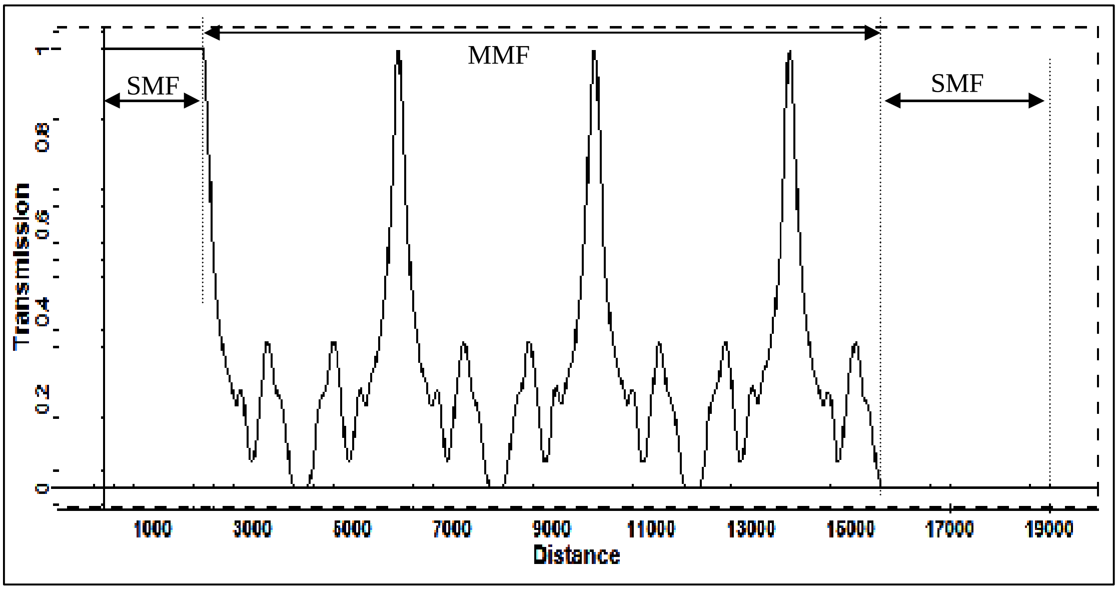
Figure (1): Schematic configuration of the single-mode–multimode–single-mode fiber structure.



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

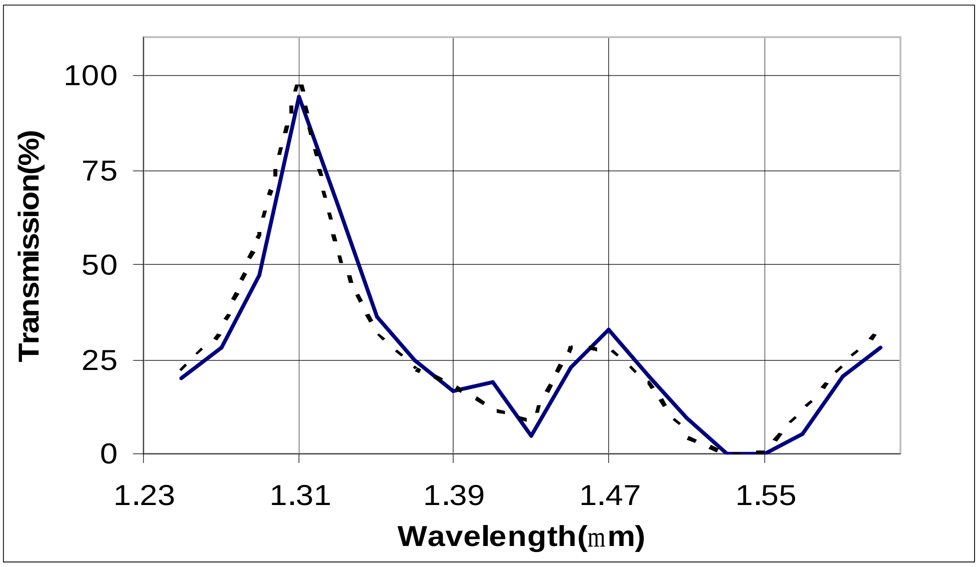


(a)



(b)

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.



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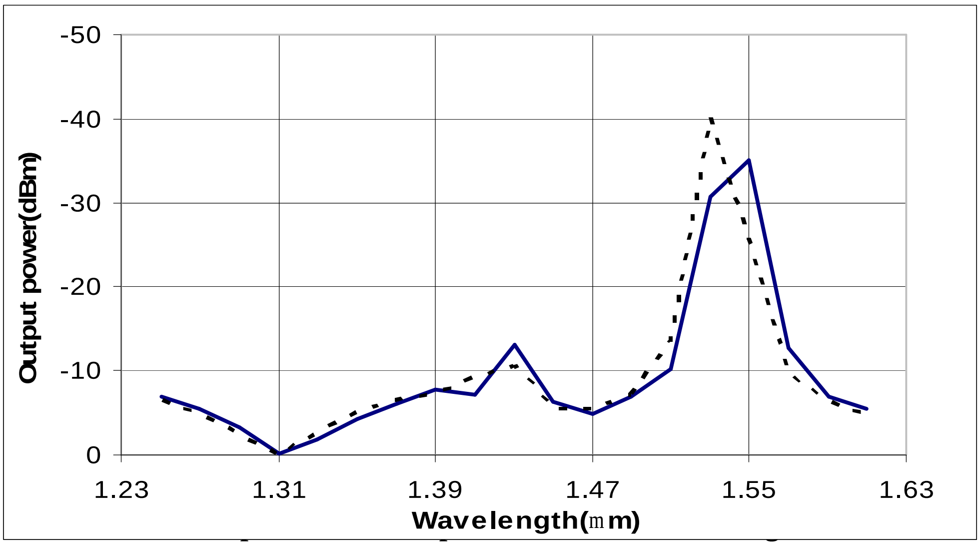


(b)

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

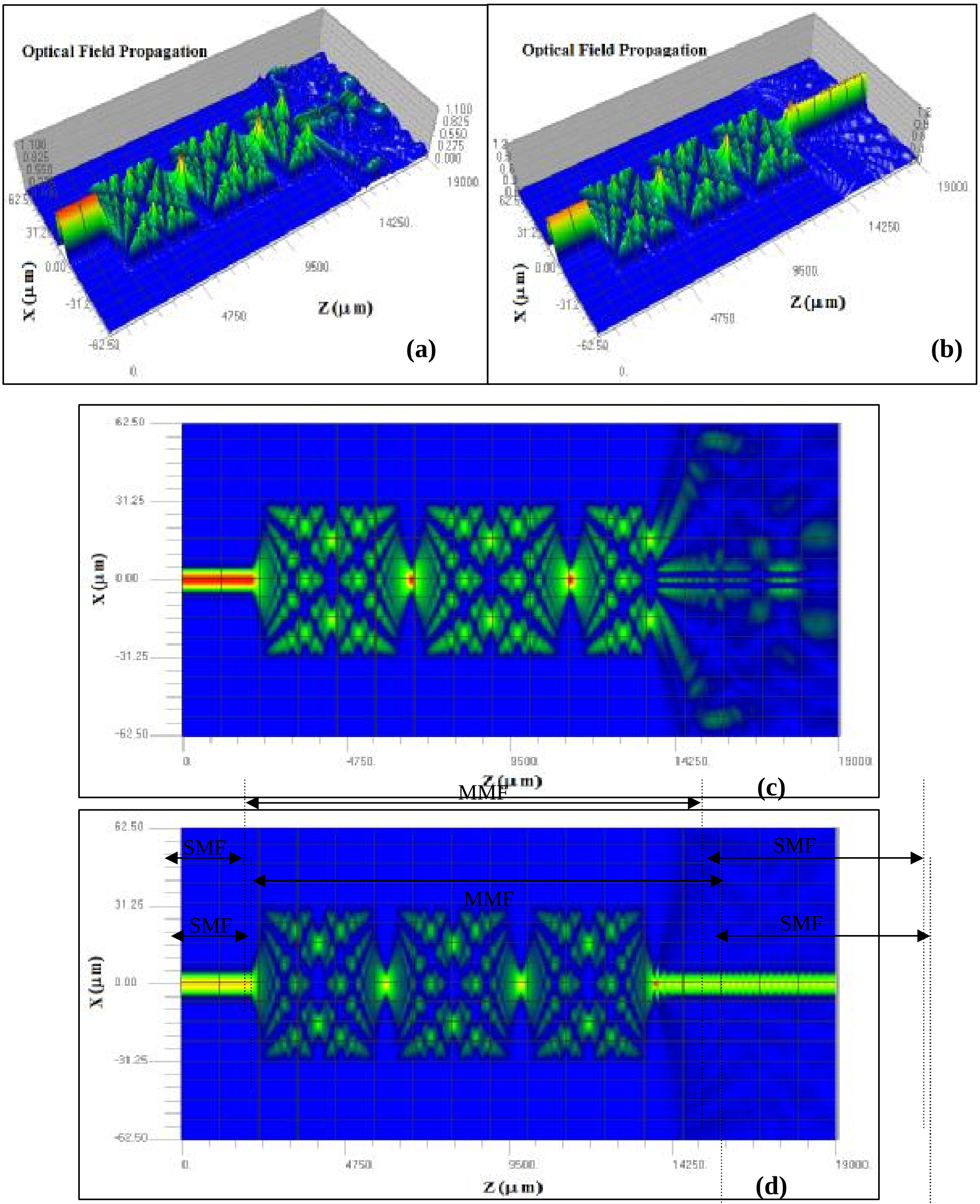
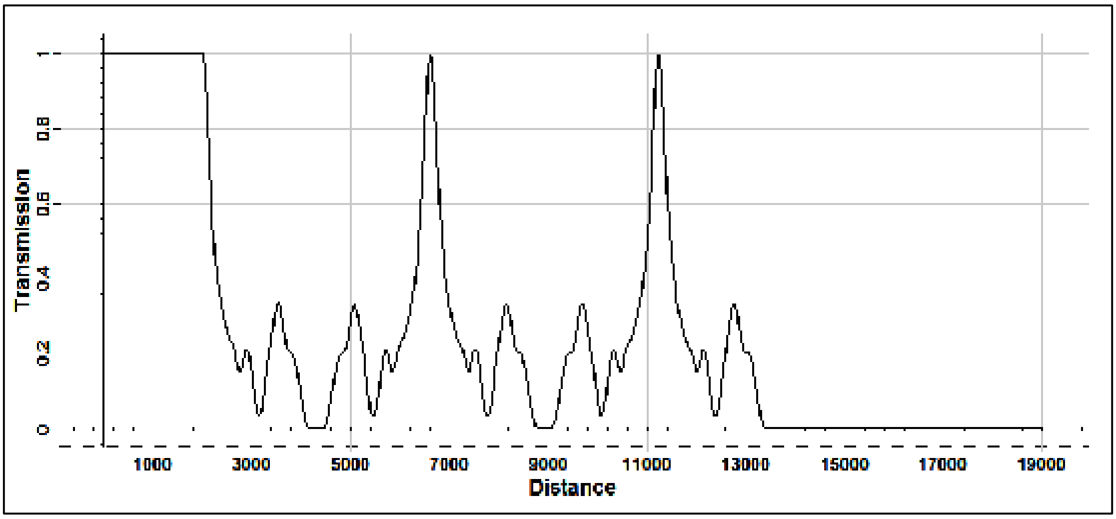
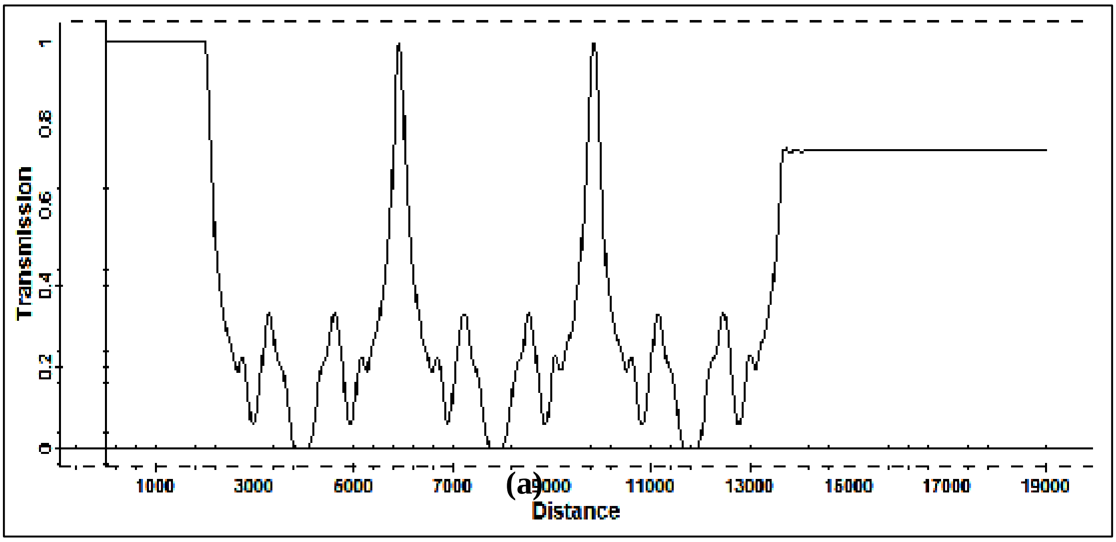


Figure (5): The propagating fields of first filter (length of MMF is 11.65 mm) at wavelengths of 1310 nm and 1550 nm. (a) & (c) Propagating fields at 1310 nm in two & three dimensions respectively, (b) & (d) Propagating fields at 1550 nm in two & three dimensions respectively

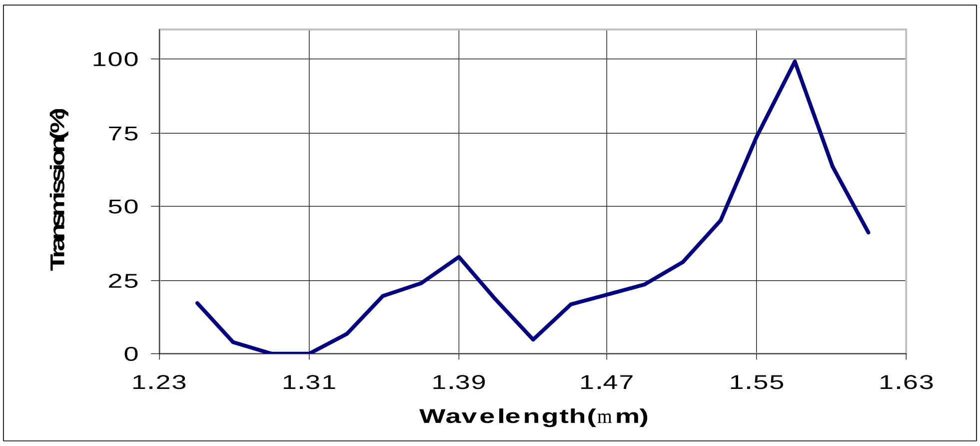


(a)



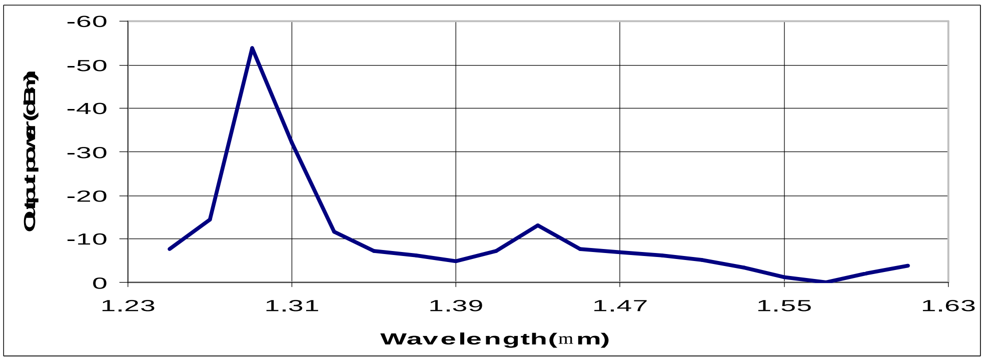
(b)

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.



(a)

(b)



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