*Preprints* (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2020

# Design of Spectral Filters Based on Mode Coupling of Optical Fibers

Ahmed A Abouelfadl and Abdullah A Alshehri
Electrical Engineering Department, Faculty of Engineering-Rabigh
King Abdulaziz university, Jeddah, KSA

## Abstract

In this paper, design of optical spectral filters based on mode coupling of optical fibers is presented. The finite difference method is applied to find the dispersion characteristics of optical fiber coupler constructing from two fibers as a composite multi-dielectric waveguide with different cores but the same cladding. Also, the field distribution for both fibers as a separate and as a composite waveguide is investigated. The spectral characteristics of the filters are computed depending on the coupling of two linear polarized modes $LP_{01}$ and $LP_{11}$. The dependence of the transmission coefficient on operating wavelengths is illustrated. Finally, the spectral bandwidth of filter as a function of the distance between the two cores is addressed.

## 1. Introduction

The rapidly increasing demand for optical signal processing and optical communication systems needs the development of the all optical fiber spectral filter characteristics which is one of the most important key passive components for optical communications and passive optical networks which mostly use wavelength division multiplexing and demultiplexing techniques. It has the advantage to integrate easily with the fiber optic networks. It also provides a low loss coupling due to its fabrication from optical fibers.

Many types of spectral filters are designed and analyzed such as: diffraction grating filters [1-3], Fabry-Perot filters [4-6], Mach-Zehnder interferometer filters [7-9], all fiber filters [9-11] and others. Most of all fiber wavelength selective filters reports on the literature consists of two or three identical fibers or two dissimilar fibers with different refractive index shapes [12-21]. The two types of these filters depend on single mode fibers supporting $LP_{01}$ in their coupling operation at range of interesting wavelengths.

In this paper, the finite difference method is used to find the optical properties of a directional coupler proposed by [22] is consisted of two dissimilar fibers, but only one fiber has single mode $LP_{01}$ and the other has dual-mode capable of supporting two modes $LP_{01}$ and $LP_{11}$. The Dispersion characteristics and field distribution of both separate fibers and as a composite waveguide are calculated by applying the finite difference method of Opti fiber software. Spectral characteristics of the coupler are investigated by using the coupled mode theory of parallel dielectric waveguides.

The paper is organized as follows.: section 2 deals with geometry and method of analysis. Discussion and numerical results are illustrated in section 3. Finally, conclusions of the work are drawn in section 4.

## 2. Geometry and Method of Analysis

The geometry of the coupler is shown in Fig.1. The geometry consists of two fibers one support single mode $LP_{01}$ called fiber1 and the other support two modes $LP_{01}$ and $LP_{11}$ called fiber2 with cladding contains the two cores.

© 2020 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2020

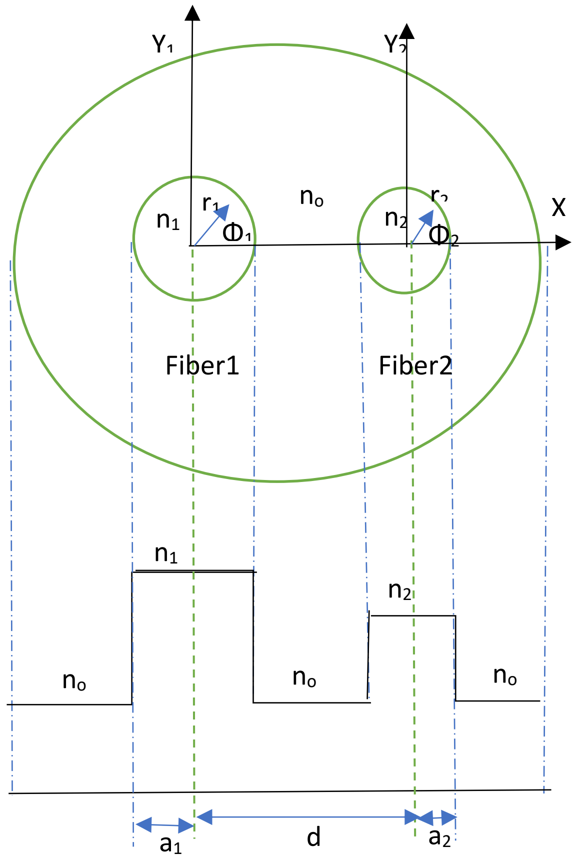


**Figure 1: Geometry of the spectral filter.**

Core radius of fiber1 is $a_1$ and for fiber2 is $a_2$. The distance between the two centers of fibers is d. The refrctive indicies $n_1$ and $n_2$ represent cores index of fiber1 and fiber2, respectively. The refrective index of the cladding is represented by $n_0$.

### 2.1 Dispersion Characteristics and Field Distributions

The weakly guiding approximation where the difference betwwen refractive index of core and cladding of each fiber is very small. So, the scalar wave analysis can be applied. The solution of this equation using Fnite Difference Method of optifiber software taking into consideration the boundary condtions of the fields between core and cladding gives the dispersion characteristics of modes $LP_{01}$ and $LP_{11}$ of fiber1 and $LP_{01}$ for fiber2. The field and power distributions of each separate fiber modes $LP_{11}$ for fiber1 and $LP_{01}$ for fiber2 are calculated. Also, the field and power distributions of composite mutidielectric waveguide are determined.

### 2.2 Spectral Characteristics of Optical Filter

The coupling mode equtions of the parallel dielctric waveguides are applied to evaluate the coupling coeffients as:

$$k_{12} = \sqrt{\frac{2(n_2^2-n_0^2)}{n_1 n_2}}\frac{K_1(w_1 d)}{K_1(W_2)\sqrt{K_0(W_1)K_2(W_1)}} \cdot \frac{U_1 U_2}{a_1 V_1}\frac{1}{U_2^2+w_1^2 a_2^2}\{w_1 a_2 K_0(W_2) I_0(w_1 a_2) + W_2 K_1(W_2) I_0(w_1 a_2)\} \quad (1)$$

$$k_{21} = \sqrt{\frac{2(n_1^2-n_0^2)}{n_1 n_2}}\frac{K_1(w_2 d)}{K_1(W_2)\sqrt{K_0(W_1)K_2(W_1)}} \cdot \frac{U_1 U_2}{a_2 V_2}\frac{1}{U_1^2+w_2^2 a_1^2}\{W_1 K_0(W_1) I_1(w_2 a_1) + w_2 a_1 K_1(W_1) I_0(w_2 a_1)\} \quad (2)$$

where:

$$U_1 = u_1 a_1 = k_0 a_1\sqrt{n_1^2 - \frac{\beta_{11}^2}{k_0^2}}$$

$$U_2 = u_2 a_2 = k_0 a_2\sqrt{n_2^2 - \frac{\beta_{01}^2}{k_0^2}}$$

$$W_1 = w_1 a_1 = k_0 a_1\sqrt{\frac{\beta_{11}^2}{k_0^2} - n_0^2}$$

$$W_2 = w_2 a_2 = k_0 a_2\sqrt{\frac{\beta_{01}^2}{k_0^2} - n_0^2}$$

$$V_1^2 = U_1^2 + W_1^2 \text{ and } V_2^2 = U_2^2 + W_2^2$$

and $k_0 = 2\pi/\lambda$ is the free space wavenumber. It can be verified from Eqns.1 and 2 that the coupling coeff-icents $k_{12}$ and $k_{21}$ are equal when $n_1 = n_2$

and $a_1=a_2$. The transmission coeffeient $T(\lambda)$ can be defined as ratio of power output from fiber1 and z=L to the power input into fiber2 at z=0.

$$T(\lambda) = \frac{|k_{12}|^2}{|S|^2} \sin^2(SL) \qquad (3)$$

where

$$S = \left[\left\{\frac{\beta_{11}-\beta_{01}}{2}\right\}^2 + k_{12}k_{21}\right]^{\frac{1}{2}}$$

The transmission coeffienct is a function of wavelength throgh S. So, the transmission coeffieient can be obtained for a specifiec wavelength range and fiber parameters. Therefore, narrowband and broadband spectral filters can be design by a suitable selection of these parameters. The coupling length $L_c$ is defined as:

$$L_c = \frac{\pi}{2S}\bigg|_{\beta_{11}=\beta_{01}} = \frac{\pi}{2\sqrt{k_{12}k_{21}}} \qquad (4)$$

## 3. Numerical Results

To assess the performance of the preposed $LP_{01}$ – $LP_{11}$ fiber coupler for applications in wavelength filtering, numerical results based on the above formulations are presented. To obtain the transmission characteristics, first dispersion chracteristics for $LP_{01}$ mode of fiber2 and $LP_{11}$ mode of fiber1 are calculated using FDM of Optifiber software. The parameters and material compostions of fibers at λ=1.33μm are summerized in Table 1. Fig.2 illustrates the dispersion characteristics for $LP_{01}$, $LP_{11}$ for fiber1 and $LP_{01}$ for fiber2.

**Table.1 Fiber parameters and matrial compositions.**

| Fiber | Core radius (μm) | Δ at λ= 1.33μm | Core material | Cladding material |
|---|---|---|---|---|
| 1 | 3.4 | 0.8% | 13.5m/o GeO2 86.5m/o SiO2 | 5.8 m/o GeO2 94.2 m/o SiO2 |
| 2 | 3.1 | 0.4% | 9.1 m/o GeO2 90.9 m/o SiO2 | |

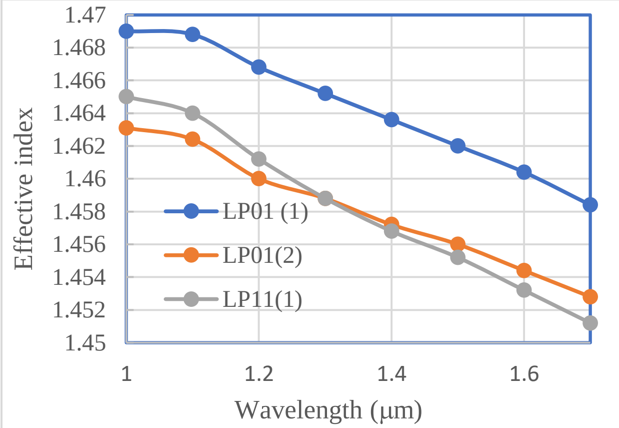


Fig.2 Dependence of effective index on wavlength

Fig.2 shows that, the effective index of LP01 mode for fiber2 equals the effective index of LP11 modes of fiber1 at λ=1.33μm. This means, these two modes have the same propagation constant and thus are phase matched at λ=1.33μm. It can be noted that, the dispersion characteristic for LP01 mode for fiber1 is not nedded in the calculation of taranmission coeffeient, but is introduced to satisfy the fact that LP01 mode of the two fibers have different propagation constants and thus do not exchange power.

Distributions of power and field across the cross section of each fiber seperatly and across the cross section of the structure at λ=1.33 are calculated using FDM of Optifiber Software as in Figs.3, 4, 5, 6 and 7.

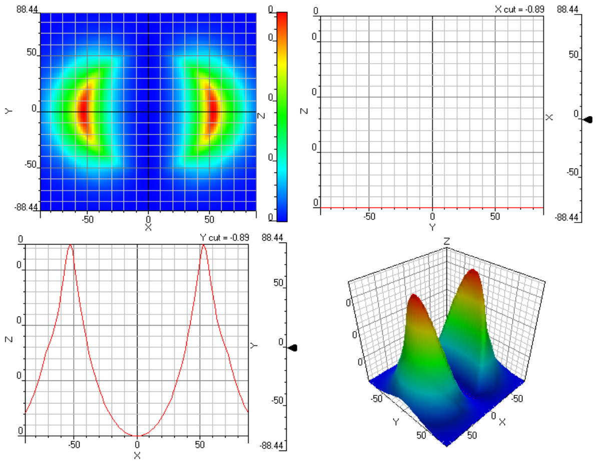

Fig.3 Power of $LP_{11}$ mode for fiber 1.

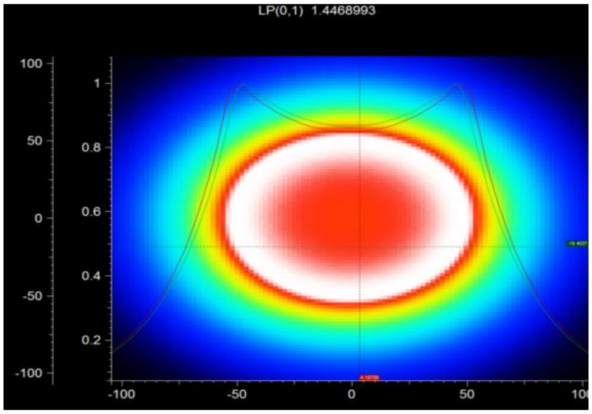


Fig. 6 Field distribution of $LP_{01}$ for fiber2.

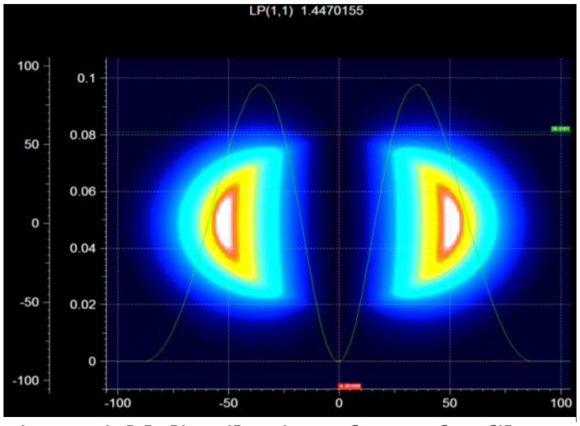


Fig. 4 Field distribution of $LP_{11}$ for fiber 1

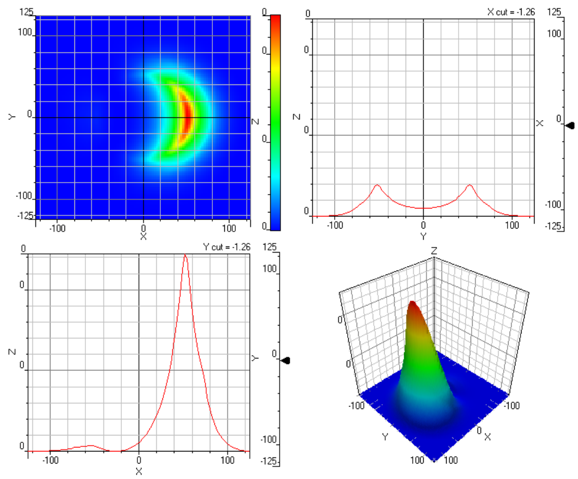

Fig.7 Power of the composite of $LP_{01}$-$LP_{11}$ across filter cross section

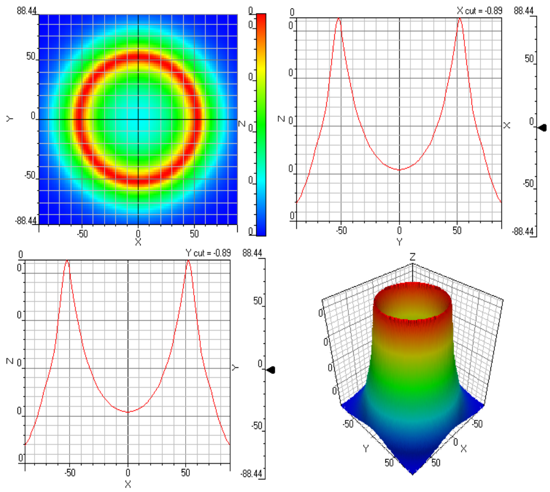

Fig.5 Power of $LP_{01}$ mode for fiber2.

Fig.8 illustrate the dependence of the spectral width of 1.33 μm speectral filter on the sepration distance d beween the centers of each core centers.

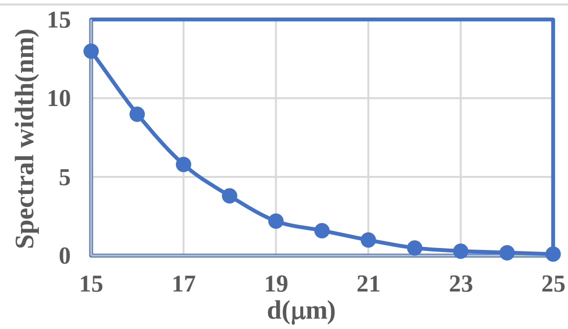


Fig.8 Dependence of spectral width on distance d.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2020

The spectral width of the filter is governed by the slop diference between the dispersion characteristics of the interaction modes as well as the core separation d. The larger the slope difference the smaller the spectral width. Also, increasing the separation distance d, produces in a decrease in spectral width. Fig.9 shows the transmission characteristic of a 1.33 μm spectral filter with fiber parameters as given in Table.1.

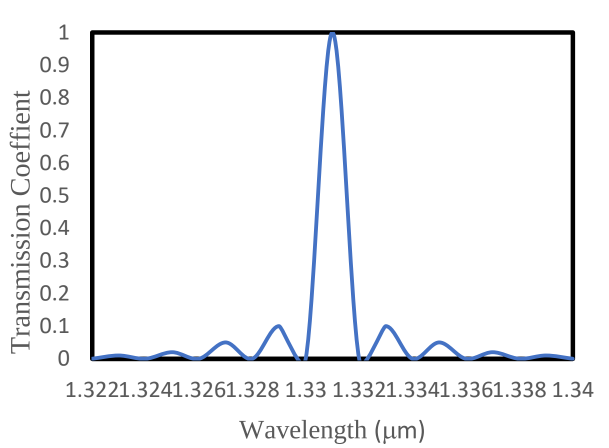


**Fig.9 dependence of transmission Coefficent on wavelength**

The peak transmission occurs at λ=1.33μm and the seperation of the two cores is d=20μm. The half power spectral width for this value of d is Δλ=1.5nm and the first side-lobe level is about 0.1. With these parameters, the coupler acts as a narrowband filter.

## 4. Conclusions

A two-fiber coupler based on LP01-LP11 mode coupling has been investigated using coupled mode theory. The coupler cross section is considered as a multidelectric waveguides for evaluating the dispersion chracteristics , power and field distributions. The finite difference method of Optifiber software is applied for solving the scalar wave equation. With a choice of appropriate parameters, the coupler can be desgined to either narrowband or broadband spectral filter. Desgin information and transmission characteristics for couplers with macimum matching at λ=1.33μm widely used wavelength in fiber optic communications were calculated. This type of spectral filter has the advantage that it can be easily fabricated and the loss of connections is very small.

## References

[1] S. B. Korovin, V. L. Smirnov, and A. V. Shmal'ko," Narrow-Band Intrfernce Holographic Filter Based on a One-Mode Fiber-Optic Light Guide", Sov. Phys. Tech. Phys., Vol. 33, No. 12, P.1466, December 1988.

[2] N. Imoto," An Analysis for Contradirectional-Coupler Type Optical Grating Filters", Technol., Vol. 3, No. 12, PP.895-900, August 1985.

[3] W. P. Huang and J. Hong," A coupled-Waveguide Grating Resonator Filter", IEEE Photonics Tech. Lett., Vol. 4, No. 8, P. 884, August 1992.

[4] S. R. Mallinson," Fiber-Coupled Fabry-Perot Wavelength Demultiplexer", Elect. Lett., Vol. 21, No. 3, PP. 121-122, January 1986.

[5] C. C. Chang," Coupled-Waveguide Fabry-Perot Resonator", M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, December 1992.

[6] J. Subias, R. Alonso, F. Villuendas, and J. Pelayo," Wavelength Selective Optical Fiber Couplers Based on Longitudinal Fabry-Perot Structures", J. Lightwave Technol., Vol. 12. No. 7, PP. 1129-1135, July 1994.

[7] N. Takato, A. Sugita, K. Onose, H. Okazaki, M. Okuno, M. Kawachi and K. Oda," 128-Channel Polarization- Insensetive Frequency Selection Switch Using High Silica Waveguides on Si", IEEE Photonic Tech. Lett., Vol. 2, No. 6, P. 441, June 1990.

[8] N. Takato, T. Kominato, A. Sugita, L. Jinguji, H. Toba and M. Kawachi," Silica Based Integrated Optic Mach-Zehnder Multi/ demultiplexer Family with Channel Spacing of

*Preprints* (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 January 2020

0.01-250 nm", IEEE J. on Sel. Areas in Comm., Vol. 8, No. 6, P. 1120, August 1990.

[9] M. Kuznetsov,"Cascaded Coupler Mach-Zehnder Channel Dropping Filter for Wavelength Division Multplexed Optical Systems", J. Lightwave Technol., Vol. 12, No. 2, PP226-230, Febryray 1994.

[10] M. S. Yataka, D. N. Payne, and M. P, Varnham," All Fiber wavelength Filters Using Concentrated Fused Taper Couplers", Electron. Lett., Vol. 21, PP. 248-249, 1985.

[11] R. Zengerle and O. G. Leminger," Wavelength Selective directional Coupler made of Non Identical Sngle Mode Fiber", J. Lightwave Technol., Vol. 4, No. 7, PP. 823-827, July 1986.

[12] A. Safaai-Jazi and J. C. McKeeman," All Fiber Spectral Filters with Nonperiodic Bandpass Characteristics and High Extinction Ratios in the Wavelength Range 0.8μm<λ<1.6μm", J. Lightwave Technol., Vol. 9, No. 8, PP. 959-963, July 1991.

[13] C. J. Chung and A. Safaai Jazi,' Narrow Band Spectral Filter Made of W-Index and step Index Fibers," J. Lightwave Technol., Vol. 10, No. 1, PP. 42-45, November 1994.

[15] Ahmed A. Abouelfadl, Sh. M. Eladl, and M. S. I. Rageh, "Optical fiber wavelength division multiplexer based on two-mode interference", Proc. of 17th National Radio Science Conference, *NRSC'2000,* Feb. 22-24, Faculty of Electronic Engineering, Minyfiya University, EGYPT, 2000, F1.

[16] Ahmed A. Abouelfadl and A. A. Saad," Study of the coupling characteristics of a two-core fiber coupler", Electronic Engineering Bulletin, No.8, July 1994, pp. 16-21, Faculty of Electronic Engineering, Menoufia University, Egypt.

[17] A. A. Saad and Ahmed A. Abouelfadl," Analysis of Similar and Dissimilar Single Mode Optical Fiber Filters", Proc. of 12th NRSC, C34, March 21-23, 1995, Alexandria, Egypt.

[18] Zhikun Xing, Xi Guo, Huabao Qin, Wei Zhang, Qizhen Sun, Kaiming Zhou, Zhou, Zhijun Yan, Deming Liu, andFiber Solc Filter Based on 45$^{o}$-Tilted Fiber Gratings," IEEE Photonics Tech. Lett., Vol. 31, NO. 20, October 15, 2019.

[19] Chuang Wu, Zhengyong Liu, Kit Man Chung, Ming-Leung Vincent Tse, Florence Y. M. Chan, Alan Pak Tao Lau, Chao Lu, and Haw-Yaw Tam," Strong LP01 and LP11 Mutual Coupling Conversion in a Two-Mode Fiber Bragg Grating", IEEE Photonics Journal, Vol.4, No.4, PP.1080-1086, August 2012.

[20] Romain Laberdesque, Antoine Monmyrant, Henri Camon, Marlene Petit, Olivier Demichel, Benoit Cluze, and Olivier Gauthier-Lafaye," Multimodal Reflectivity of CRIGF Filters: First Experimental Observation and Modelling", ICTON 2015.

[21] Pengfei Ge, Xiao Liang, Jiaheng Wang, Chunming Zhao, Xiqi Gao, and Zhi Ding," Optical Filter Designs for Multi-Core Visible Light Communication", IEEE Transaction on Communications, Vol. 67, No. 3, PP.2173-2187, March 2019.

[22] J. Jagannathan and A. Safaai Jazi," All-fiber spectral filter based on $LP_{01}$-$LP_{11}$ mode coupling", Proceedings IEEE SOUTHEAST CON '97, PP.154-156, 1997.

.