OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 11, No. 11-12, November-December 2017, p. 628-632

A seven-core-fiber spectral filter based on LP_{01}-LP_{01} mode coupling

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A multi-core fiber (MCF) structure with a new filtering concept based on core-to-core coupling is proposed. With the proper choice of the multi-core fiber's geometry, filters can be constructed by splicing two identical, axially aligned, single-mode fibers (SMFs) to both ends of a seven-core fiber (7CF) with length L in the form of a chain: SMF-7CF-SMF (S7S). The eigen-mode expansion method is used to model the propagation of light in these filters. The proposed device is useful as a bandpass/bandstop filter in optical fiber communications systems.

(Received March 20, 2017; accepted November 28, 2017)

Keywords: Multi-core fiber (MCF), Eigen-mode expansion (EME), Fiber-optic device, Wavelength filter

1. Introduction

Fiber spectral filters based on multi-core fibers (MCFs) offer an efficient solution for separating out or transmitting a certain range of wavelengths in an optical signal and can be easily implemented into fiber links. Special fibers such as a nine-core Ge-doped fiber [1], photonic crystal fiber couplers [2], dual-core [3], triple-fiber couplers [4], dissimilar core fiber couplers [5] and concatenated fused-taper couplers [6] have been used as optical fiber filters.

Bandpass filters constructed by splicing a small length of multimode fiber (MMF) in between two identical single-mode fibers (SMFs) have been reported [7], [8]. This is known as an SMS structure. Replacing the MMF section in the previously mentioned SMS structures with a seven-core fiber increased the number of degrees of freedom for constructing and manufacturing both optical filters and optical couplers. The coupled modes can be controlled by varying the size, index profiles, arrangement, the separation of the cores and the length of the MCF.

For MCFs the light propagates through multiple cores as a supermode and every supermode can be considered as one spatial channel [9]. The number and characteristics of the supermodes depend on the number of cores, their size, placement, index profiles, and the core separation.

The proposed filter consists of two identical single-mode fibers spliced (axially aligned) at both ends of a 7CF with length L in the chain SMF-7CF-SMF (S7S). The central core of the 7CF is excited by the fundamental mode of the single-mode fiber input. In this case, only two supermodes that are circularly symmetric with nonzero intensity in the central core will be excited. Then, after a distance z, the power is transferred from the central core to the other cores and the optical field oscillates between a state where all the power is in the central core (the initial state at z=0) and a state where one-seventh of the power is distributed between the outer cores and the central core [10]. The two supermodes propagate with different propagation constants. The wavelength dependence of the propagation constants for supermodes is presented in [11]. Since the power is distributed throughout the two interfered supermodes and the wavelength dependence of this interference, the transmitted power through a S7S structure is highly sensitive to the wavelength of the operation. Therefore, the S7S structure can be used for designing novel spectral filters.

A MCF containing seven cores has an advantage compared to a three-core fiber due its symmetry. This symmetry makes the filter insensitive to the polarization of the input light.

The paper is structured as follows. In Sections 2 and 3 the fundamentals of the 7CF's structure and an analysis of mode-coupling dynamics in 7CFs are presented on the basis of coupled-mode theory. Then, in Section 4, the numerical simulations of the S7S device using a 3D full-vectorial model based on the eigen-mode expansion (EME) method is illustrated. In Section 5 the simulation results obtained with FIMMWAVE and FIMMPROP will be discussed. Finally, the conclusions will be drawn.

2. Fundamentals of seven-core fiber

Of all the MCF structures we consider the homogenous, identical, 7-core MCF consisting of one central core labeled (1) that is concentrically surrounded by a hexagonally distributed six cores, labeled (2–7) as shown in Fig. 1. For the simplicity of the design and fabrication, we assume that each core has an identical diameter and refractive index, d_c and n_{co}, respectively, while the cladding has a refractive index of n_{cl}. It is also assumed that the MCF cross-section is uniform along the *z*-axis and each individual core supports only one fundamental guided mode (LP_{01}). If the amplitude of the fundamental mode of the *p* core is $A_p(z)$, the propagation constant for the fundamental mode of core p is β_p then the electric and magnetic fields in the pth core can be written in terms of its mode amplitude function in the cross-section multiplied by the propagating function in the z direction as

$$\vec{E}_p(z) = \vec{A}_p(z) e^{-j\beta_p z} \quad (1)$$

$$\vec{H}_p(z) = \vec{A}_p(z) e^{-j\beta_p z} \quad (2)$$

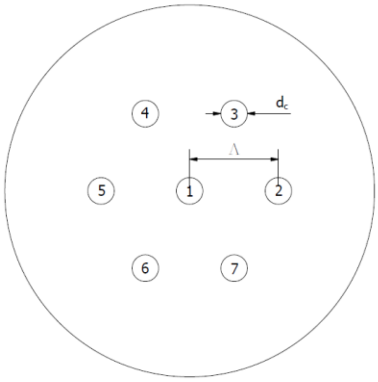

Fig. 1. Seven-core fiber structure consisting of 6 cores symmetrically distributed around a central core

The interaction between the modes of the 7CF is given by a set of coupled-mode equations [12-17], which can be written in matrix form as

$$\frac{d\,\vec{A}(z)}{dz} = -C\,\vec{A}(z) \quad (3)$$

where $\vec{A}(z) = [\vec{A}_1(z)\,\vec{A}_2(z).....\vec{A}_7(z)]^T$ is the amplitude of the transverse electric field at position z for each core and the superscript T denotes the transpose of the matrix or vector, z is the direction of propagation, and C is the coupling matrix that describes the interaction between pairs of cores whose separation is Λ. The coupling matrix is given by

$$C = j\begin{bmatrix} 0 & k & k & k & k & k & k \\ k & 0 & k & 0 & 0 & 0 & k \\ k & k & 0 & k & 0 & 0 & 0 \\ k & 0 & k & 0 & k & 0 & 0 \\ k & 0 & 0 & k & 0 & k & 0 \\ k & 0 & 0 & 0 & k & 0 & k \\ k & k & 0 & 0 & 0 & k & 0 \end{bmatrix} \quad (4)$$

All the works reported for the calculation of the coupling coefficient were performed by using numerical approaches, e.g., finite element, or by using analytical approximations, or a combination of both.

The coupling coefficient between two parallel single-mode waveguides can be calculated using a rigorous definition in terms of the overlap integral [10], [11]:

$$k_{pq} = \frac{\omega\varepsilon_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} (n_{co}^2 - n_{cl}^2) E_p^* E_q^* dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} u_z (E_p^* \times H_q - E_p \times H_q^*) dxdy} \quad (5)$$

where E_p, E_q, H_p, H_q are the electric and magnetic field distributions of the LP_{01} mode of the cores p, q respectively.

3. Analysis of the mode coupling dynamics in a 7CF

In a homogenous 7CF in which all the cores have equal sizes and six are symmetrically arranged around the central core, there are only two coupling coefficients in the structure, i.e., one for the coupling between two adjacent external cores and another for the coupling between the central and the external cores. The coupling coefficient of the non-adjacent cores can be neglected; therefore, the 7-by-7 system of coupled differential equations obtained from Eq. (3) reduces to two equations that can be solved analytically for the amplitude of the electric field in the central and (any of the) external cores [19]:

$$A_1(z) = [(\cos(\sqrt{7}kz) + \frac{i}{\sqrt{7}}\sin(\sqrt{7}kz)]\exp^{-ikz} \quad (6)$$

$$A_p(z) = \frac{-i}{\sqrt{7}}\sin(\sqrt{7}kz)\exp^{-ikz} \qquad p\neq 1 \quad (7)$$

In the experimental situation the MCF section is spliced between two single-mode fibers (SMFs). The excitation radiation is launched only into the central core, i.e., $A_1(0)=1$ and $A_p(0)=0$ for all the external cores.

Since the normalized power $P = |A|^2$ a simple expression for the z evolution of the normalized mode power can be obtained as

$$P_1(z) = |A_1(z)|^2 = \frac{1}{7} + \frac{6}{7}\cos^2(\sqrt{7}kz) \qquad (8)$$

$$P_p(z) = |A_p(z)|^2 = \frac{1}{7}\sin^2(\sqrt{7}kz) \qquad p \neq 1 \qquad (9)$$

This leads to a periodic exchange of power between the cores along the length of the fiber.

4. Eigen-mode expansion method

In this section the EME method is used to model the field propagation in the S7S device. The EME method has been well known in photonics for some time through the film-mode-matching (FMM) method [20], [21]. It is based on the idea that any solution of Maxwell's equations in the region of the waveguide can be written in terms of a superposition of the forward (propagating along +z) and backward (propagating along -z) propagating modes. The field in any section can be written as a linear combination of the 2D eigen modes with the corresponding propagation constants β_k. Such modes can be calculated using Fimmwave's mode solvers:

$$\psi(x,y,z) = \sum_{i=1}^{N}\left(c_i^f e^{j\beta_i z} + c_i^b e^{-j\beta_i z}\right)\psi_i(x,y) \qquad (10)$$

where $\psi_i = [\vec{E}_i, \vec{H}_i]$ is the mode profile, β_k is the corresponding propagation constant, and c_i^f, c_i^b are the forward and backward complex amplitude coefficients of the i^{th} mode, respectively.

The schematic of the structure used to simulate the coupling and the power transferred between the cores in the 7CF is shown in Fig. 2. The structure consists of a small length of 7CF in between two identical SMFs. The light is coupled into the input central core using a 4.8-μm single-mode input fiber. The power then couples up to the surrounding cores along the length of the 7CF. Finally, the transmission power is collected from the "straight" and "offset" single-mode output waveguide having a similar radius to the single-mode input fiber and the cores in the 7CF section.

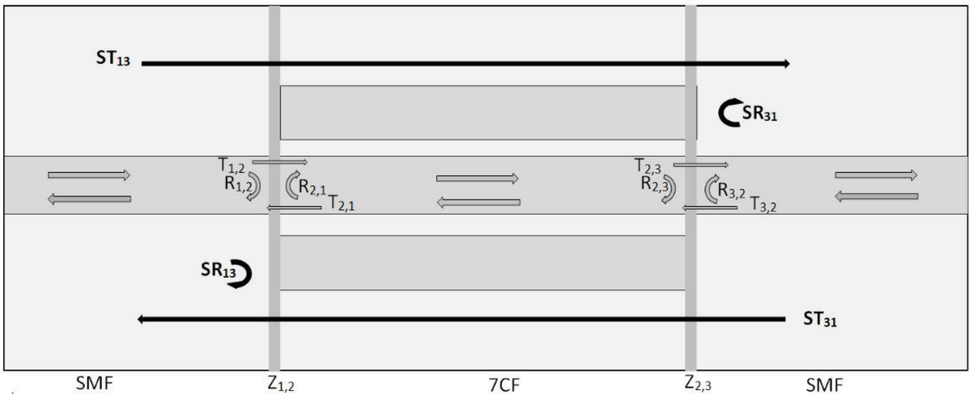

Fig. 2. Various reflections and transmissions in a S7S device

The fields in the entire device are obtained using the scattering-matrix approach involving both forward and backward modal excitations for the field in each of these sections and applying the continuity and the orthogonality conditions for the mode fields across the interface between consecutive sections to express the fields traveling away from the joint in terms of the fields incident on the joint. The tangential electric fields must be the same on each side of the interface

$$\sum_{i=1}^{N}\left(a_i^f e^{j\beta_i z} - a_i^b e^{-j\beta_i z}\right)E_{i,t}^m(x,y) = \sum_{i=1}^{N}\left(b_i^f e^{j\beta_i z} - b_i^b e^{-j\beta_i z}\right)E_{i,t}^{m+1}(x,y) \qquad (11)$$

$$\int_{-\infty}^{\infty}(E_{x,i}.H_{y,j} - E_{y,i}.H_{x,j}).ds = \delta_{ij} \qquad (12)$$

where a_i^f, a_i^b are the coefficients of the forward and backward modes at the beginning of section m and b_i^f, b_i^b are the coefficients of the forward and backward modes at the beginning of section m+1. $E_{i,t}^m(x,y), E_{i,t}^{m+1}(x,y)$ are the tangential electric mode fields on the consecutive sections m, m+1. The joint scattering matrix expresses the fields travelling away from the joint in terms of the fields incident on the joint as in [22].

Since the S7S device is described by three sections separated by two joints $z_{1,2}$ and $z_{2,3}$, this necessitates calculating the scattering reflection matrices (SR_{13} and

SR_{31}) and the scattering transmission matrices (ST_{13} and ST_{31}). Then the S-matrix for the whole device can be computed by combining them using the 3D full-vectorial eigenmode expansion simulator in the FIMMPROP module from Photon Design.

5. Results and discussion

In order to simulate the propagation dynamics of the 7CF design based on Table 1 as a function of the fiber length at a wavelength of 1550 nm the light is launched into the central core of the MCF, i.e., $A_1(0)=1$. Then, the transmitted power in every core is detected by an "offset" single-mode waveguide that has a radius similar to that of the cores in the 7CF. The result is presented in Fig. 3. This figure shows how the power transfers to the outer cores after the coupling length and then swings back again along the length of the 7CF.

Table 1. MCF parameters and their values

Parameter	Value
d_c	4.8 [um]
Λ	30 [um]
n_{co}	1.46159
n_{cl}	1.45709

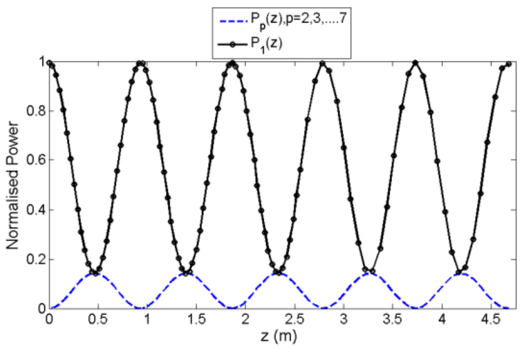

Fig. 3. Propagation dynamics of a homogeneous seven-core MCF for the case of light injected into the central core

To further numerically simulate the transmission characteristics of the proposed S7S device, we define the transmission function T_p (λ) for the p^{th} core as the ratio of the power output from this core to the power input into the central core at z = 0.

Next, we set the 7CF's length to an integer multiple of the coupling length and run the simulation to scan the transmittance in all cores as a function of the wavelength. The results are shown in Fig. 4. The spectral characteristics in Fig. 4 show the variations of the transferred power from the central core into the external cores versus the wavelength. The important feature in Fig. 4 is the case corresponding to the peak transmission at a wavelength of 1550 nm. Therefore, the selectivity of the wavelength is based on the principle that light directed into the central core will pass through it and reach its end, except for certain wavelengths where it will couple and appear at the end of the other cores.

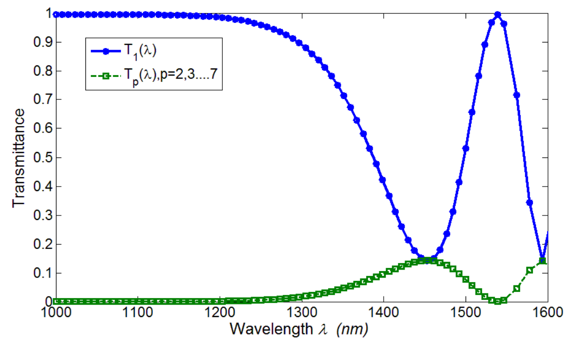

Fig. 4. Transmittance characteristic of the central and the outer cores. The parameters of the fiber are defined in Table 1.

6. Conclusions

A new type of fiber-optic device based on a S7S structure is proposed. The device can be used as a bandpass filter for shorter wavelengths, the bandwidth is up to 300 nm (from 1000 nm to 1300 nm), if the central core of the second end in the 7CF is spliced to a SMF. To achieve a bandstop filter with full width at half maximum (FWHM) equal to 80 nm one of the external cores of the second end in the 7CF is spliced to a SMF.

In the future, we intend to measure the transmission characteristics of the proposed S7S device. The measurements can be made by splicing a conventional single-core, step-index, single-mode fiber to the central core of the 7CF, a broadband light source and an optical spectrum analyzer for measuring the transmitted light.

Acknowledgments

The authors would like to thank the Optacore team for supplying the seven-core fiber to acquire knowledge about spectral filtering. This work was supported by the Slovenian Research Agency (ARRS) as part of the "Algorithms and optimization procedures in telecommunications" programme.

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