Original scientific paper

Informacije MIDEM
Journal of Microelectronics,
Electronic Components and Materials
Vol. 47, No. 1(2017), 49 – 54

A seven-core fibre for fluorescence spectroscopy

Ahmed Samir[1, 2], *Boštjan Batagelj*[1,3]

[1]*University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia*
[2]*Ain Shams University, Faculty of Science, Physics Department, Cairo, Egypt*
[3]*Centre of Excellence for Biosensors, Instrumentation and Process Control, Ajdovscina, Slovenia*

Abstract: Fibre-optic fluorescent probes need special filtering; this allows them to reject the strong excitation light while transmitting the weak fluorescent light to the detector. In this paper, a seven-core fibre with optically coupled cores is proposed for fluorescent probes. Using core-to-core mode coupling for filtration instead of mounting conventional filters would decrease the number of necessary parts and the size of the probe, making it suitable for spectroscopic applications. The proposed probe was assembled with the central core being used to transmit and couple the excitation radiation to the outer six cores. Using all the cores for delivering the excitation light from the source to the sample reduces the risk of sample being photochemically damaged compared to excitation by a single-core fibre. Fluorescence emission feedback radiation at a higher wavelength can be collected in the outer six cores, and then the fluorescence signal can be coupled from these cores to the central core. The results from the numerical simulations of the 3D full-vectorial model show two cases corresponding to peak transmission at wavelengths of 410 nm and 480 nm. Therefore, the selectivity of the wavelength ensures that the light directed into the central core will pass through it and reach the end of the probe, except for certain wavelengths, where it will couple and appear at the end of the other cores.

Keywords: multi-core fibre (MCF); fluorescent probe; wavelength filtering devices; spectral filtering

Sedem-jedrno vlakno za fluorescenčno spektroskopijo

Izvleček: Fluorescenčne sonde iz optičnega vlakna potrebujejo posebno filtriranje, ki omogoča zavračanje močne vzbujevalne svetlobe medtem ko na detektor prepušča šibko fluorescenčno svetlobo. V tem prispevku je za fluorescenčno sondo predlagano sedem-jedrno vlakno z optično sklopljenimi jedri. Uporaba rodovnega sklapljanja iz jedra na jedro za filtracijo namesto montaže običajnih filtrov zmanjša število potrebnih sestavnih delov in velikost sonde, ki je primerna za uporabo v spektroskopiji. Predlagana sonda je sestavljen iz osrednjega jedra, ki se uporablja za oddajanje in sklapljanje vzbujevalnega sevanja na zunanjih šest jeder. Uporaba vseh jeder v primerjavi z enim samim jedrom vlakna za dostavo vzbujevalne svetlobe od vira do vzorca zmanjša tveganje za fotokemično poškodovanje vzorca. Povratno sevanje fluorescenčne oddaje, na višjih valovnih dolžinah, se lahko zbira v zunanjih šestih jedrih od koder je nato sklopljeno v osrednje jedro. Rezultati numeričnih simulacij s tridimenzionalnim popolnoma vektorskim modelom prikazujejo dva primera, ki ustrezata največji propustnosti pri valovnih dolžinah 415 nm in 480 nm. Pri tem selektivnost valovne dolžine omogoča da bo svetloba usmerjena v osrednje jedro prehajala skozenj in dosegla konec sonde, medtem ko se nekatere valovne dolžine sklopijo in pojavljajo na koncu drugih jeder.

Ključne besede: večjedrno vlakno, fluorescenčna sonda, naprave za filtriranje valovnih dolžin, spektralno filtriranje

** Corresponding Author's e-mail: ahmed.samir@fe.uni-lj.si*

1 Introduction

Optical fibres have been used in many sensing applications [1-2]. Fluorescence-based optical-fibre sensors are of special interest because of their various applications in non-invasive, in-vitro/in-vivo detection systems, drug discovery, the analysis of biomolecules for disease diagnostics, environmental monitoring, three-dimensional, in-situ analyses of living organisms, and the investigation of tissues [3-6].

Fluorescence measurement techniques with free beam optics have many optical components, such as an off-axis parabolic reflector and dichroic beam splitters. This bulky optical arrangement requires a precise optical alignment. Fluorescence-based optical fibre measurement techniques are more convenient compared to fluorescence-based, free-beam optics techniques due to their flexibility, immunity to external electromagnetic interference, cost-effectiveness, compactness, small size, remote-monitoring capability, long-range operation and their ability to operate in harsh environments. Several configurations of fibre probes for fluorescence spectroscopic systems have been employed. The first configuration consists of a single-fibre probe: the same fibre is used to deliver the excitation radiation to the sample and to collect the emitted radiation.

In the second configuration one fibre is used to transmit the excitation radiation to the sample and a second fibre is used to collect and guide the emission radiation to the detection system. Using separate fibres eliminates the need for fibre splitters, but decreases the chances of capturing the emission photons, as only a small portion of the excited fluorescence can be collected.

In the third configuration fluorescence measurements are made with fibre bundles, where half of the fibres carry the excitation radiation, while the other half return the emission radiation [7, 8]. There are also other designs that include a central excitation fibre surrounded by a number of collection fibres located in one or more rings known as collection rings [9].

In the fourth configuration, probes based on a multicore-coupled structure have been proposed [10]. Multi-core fibres (MCFs) have many advantages over fibre bundles, such as an increased stability, as each core will undergo the same environmental changes, like temperature increases, vibrations and pressure changes. The overall size is also reduced; this is because multiple cores can be designed in a fibre with the same width as a single-core fibre. The core separations throughout the fibre are constant, compared to fibre bundles made by inserting multiple single-core fibres into a capillary, and adding extra functionality to MCFs is easier and more readily repeatable than for a fibre bundle. It also offers new opportunities. The first opportunity is the sinusoidal spectral response due to the coupling between the cores, which allows correlating the property being measured with either the intensity changes or the spectral shifts over the section of the sinusoidal. They have been widely used in a variety of different applications, such as fibre sensors [11], spatial division multiplexing [12], microwave photonics [13], fibre lasers [14], and amplifiers [15].

Our objective is to introduce a new type of optical fibre, with novel capabilities for fluorescence detection, as shown in Fig. 1. One advantage of our proposed MCF probe is the use of core-to-core coupling for filtration instead of external conventional filters. Fluorescence-based, optical-fibre probes with conventional external filters require proper fixations and careful positioning. Another limiting factor that applies to the filters is the outer diameter of such probes. For these reasons, the replacement of the conventional external filters with another, alternative filtering is still of interest [16, 17]. The integration of fibre Bragg gratings into the fibre cores has already been suggested [18, 19]. The challenge is, however, to optimize the filtering characteristics of the MCF filter in order to match the excitation/emission wavelength fingerprint of any selected fluorophore. Therefore, MCF filters with different structures resulting in appropriate optical properties have to be designed and the optical filtering characteristics must be determined to enable the fabrication of the optimal filter for the detection of a selected fluorophore.

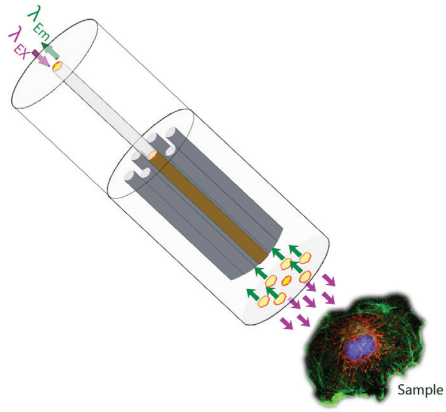

Figure 1: Seven-core fibre for sending the excitation light to the fluorophore and collecting the emitted fluorescence light.

Here, we focus on the design of a seven-core fibre with coupled cores that we intend to use as a probe for fluorescence spectroscopy. The paper is structured as follows. In Section 2 the fundamentals of the seven-core fibre structure are presented on the basis of the Eigen mode expansion theory. Then, in Section 3, the numerical simulations of the complete modal analysis via a 3D full-vectorial model based on the EME method is used to illustrate the modal characteristics of the super modes inside the MCFs. In Section 4 the simulation results obtained by FIMMWAVE and FIMMPROP will be discussed. Finally, the conclusions will be drawn.

2 Fundamentals of seven-core fibres

MCFs can be classified into three categories: multicore, single-mode fibres with coupled cores; multicore, single-mode fibres with uncoupled cores; and multicore few-mode fibres. For all the MCF structures we consider the homogenous, identical, 7-core MCFs consisting of one central core labelled (1) concentrically surrounded by hexagonally distributed six cores labelled (2–7) as shown in Fig. 2. For simplicity of design and fabrication, we assume that each core has an identical radius and refractive index r_{co} and n_{co}, respectively, while the cladding has a refractive index of n_{cl} as in Table 1. The values of refractive indexes correspond to fluorine-doped fi-

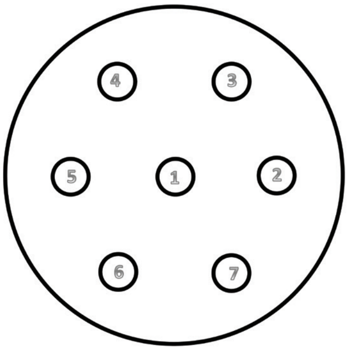

Figure 2: Seven-core coupled structure consisting of 6 cores symmetrically disposed around a central core.

bre [20] at the wavelength 415 nm. It is also assumed that the MCF cross-section is uniform along the *z*-axis.

Table 1: MCF parameters and their values.

Parameter	Value
r_{co}	2 [μm]
Λ	7 [μm]
n_{co}	1.45125
n_{cl}	1.449

3 The 3D full-vectorial Eigen Mode Expansion (EME) method

In this section the EME method is used to model the field propagation in the MCFs. The EME method has been well known in photonics for some time through the film-mode matching (FMM) method [21], [22]. 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 [23]. The field in any section can be written as a linear combination of the 2D eigenmodes with the corresponding propagation constants β_k. Such modes can be calculated using Fimmwave's mode solvers:

$$\boldsymbol{\psi}(x,y,z)=\sum_{i=1}^{N}(C_i^f e^{j\beta_i z}+C_i^b e^{-i\beta_i z})\boldsymbol{\psi}_i(x,y) \qquad (1)$$

where $\boldsymbol{\psi}_i$=[E_i , 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.

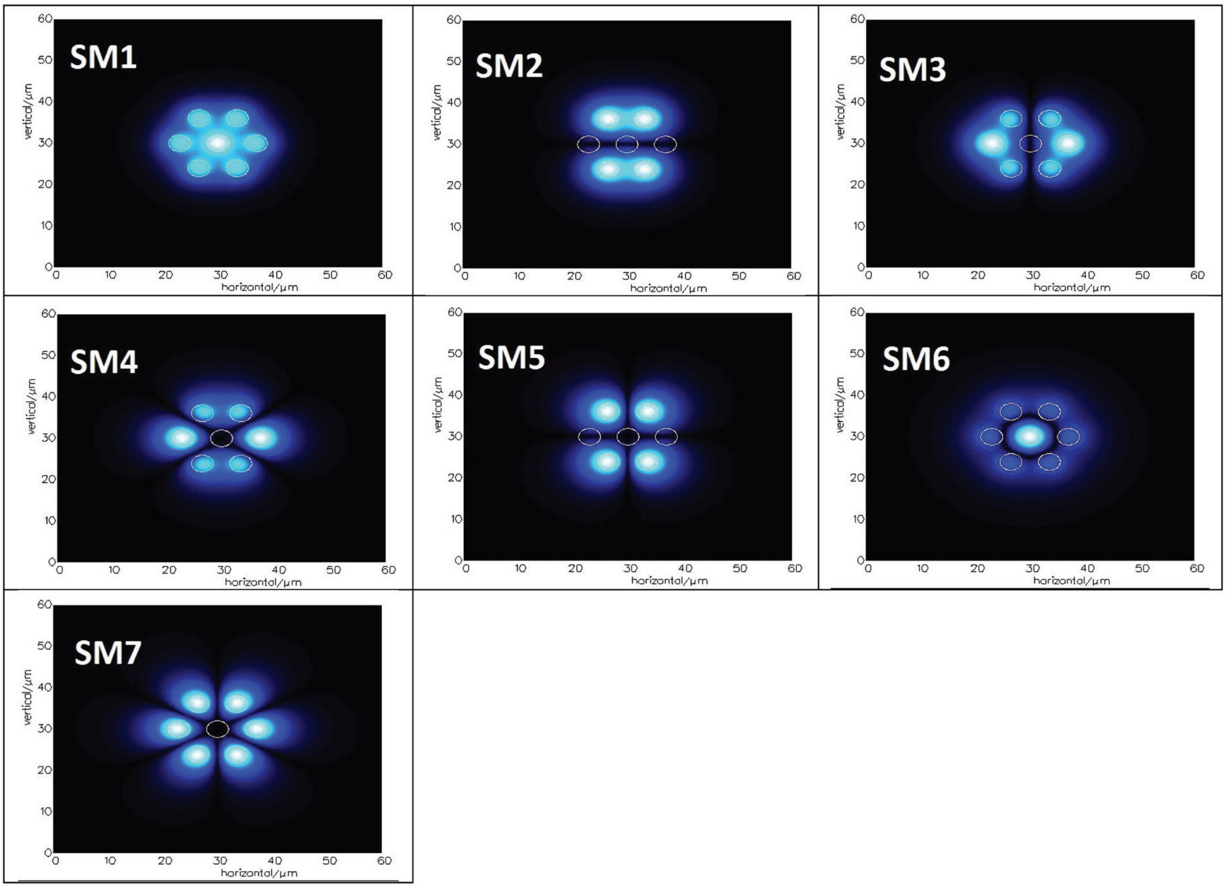

Figure 3: Electric field of the seven super-modes using a finite-element mode solver.

For MCFs with coupled cores, the pitch distance between the cores is reduced in order to increase the core-to-core coupling. As a result, evanescent core coupling occurs and light propagates through all the cores as a super-mode. Each super-mode is a linear superposition of the individual core modes. The total number of non-degenerate super-modes equals the number of cores. The super-mode patterns are calculated using a finite-element mode solver (Fimmwave by Photon Design). The intensity patterns for the seven super-modes of the seven-core fibre design based on table 1 are shown in Fig. 3.

In theory, if the excitation radiation is only launched into the central core, only the super-modes with none zero intensity in the centre core, performing the mode-overlap conditions, can be excited. These modes are SM_1 and SM_6 in Fig. 3.

Currently, analytical expressions have been proposed for the propagation constants and the super-modes inside the MCFs with circularly distributed cores [24-27]. In addition, a semi-analytical model [28] was calculated for the transmission of light in the MCF using the equation

$$T(\lambda) = 1 - P_1 P_6 sin^2\left(2\sqrt{7}\,C(\lambda)L\right) \quad (2)$$

where P_1 and P_6 are the fraction of light carried by the super-modes SM_1 and SM_6, respectively, C is the core-coupling coefficient and L is the MCF segment length.

4 Simulation results and discussion

The methodology was applied to simulate different designs of seven-core fibre by changing the lattice parameters, core diameters and scanning the transmittance in the external cores and the central core of the MCF in a certain range of wavelengths until we reach the optimum design, which matches the excitation/emission wavelength fingerprint of any selected fluorophore.

In order to simulate the propagation dynamics of the seven-core fibre design based on table 1 as a function of the fibre length for a wavelength of 415 nm the light 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 having a radius similar to that of the cores in the MCF. The result is presented in Fig. 4. This figure shows how the power transfer to the outer cores after the coupling length and then swings back again along the length of the MCF.

To further numerically simulate the transmission characteristics of the proposed seven-core fibre, we define

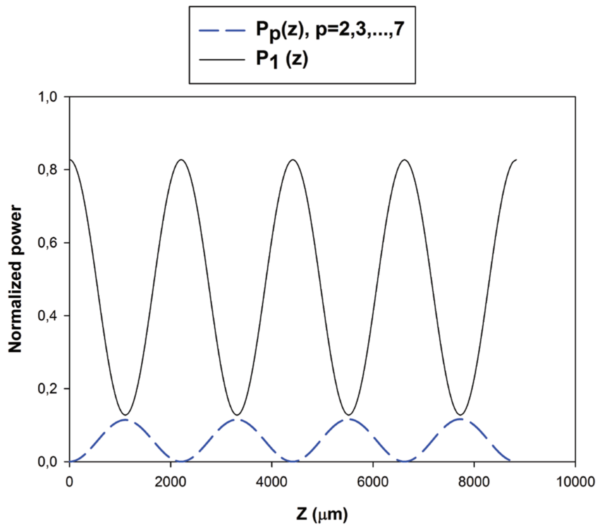

Figure 4: Propagation dynamics of a homogeneous seven-core MCF for the case of light injected into the central core.

the transmission function $T_p(\lambda)$ 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 MCF length to an integer multiple of the coupling length and run the simulation to scan the transmittance in all the cores as a function of the wavelength. The results are shown in Fig. 5. The important features in Fig. 5 are the two cases corresponding to the peak transmission at wavelengths of 365 and 410 nm. Therefore, the central core can be used to transmit and couple the excitation radiation of 365 nm to the outer six cores. Using all the cores for delivering the excitation from the light source to the sample in comparison to excitation by a single-core fibre reduces the risk

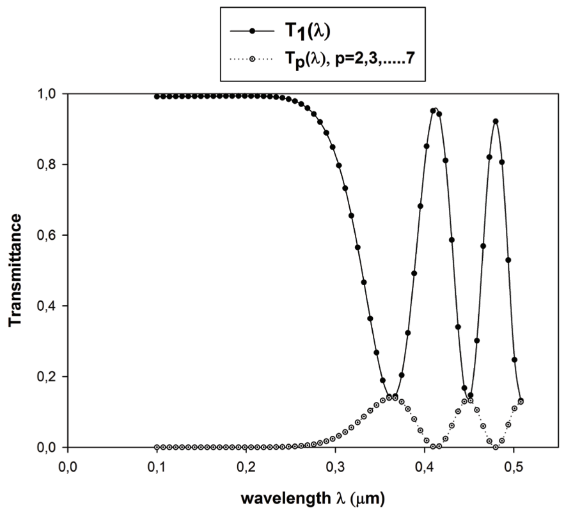

Figure 5: Transmittance of the central core and the outer cores as a function of the wavelength.

of the sample causing photochemical damage due to high light power density. Then the fluorescence emission feedback radiation (415 nm) can be collected in the outer six cores, and the fluorescence signal can be coupled from these cores to the central core.

5 Conclusions

A novel type of fibre probe has been proposed. It can be used for many applications such as efficient fluorescence signal collection and spectral filters. With an appropriate choice of parameters, the probe can be designed to offer a narrowband spectral filter.

Changing the optical or geometrical parameters influences the effective refractive index of the coupled modes and therefore leads to variations in the coupling coefficient and the overall response of the coupled system.

One obvious challenge is to optimize the filtering characteristics of the MCF filter in order to match the excitation/emission wavelength fingerprint of any selected fluorophore. This can be done by changing the geometrical parameters of the MCF probe.

Our future work will be to splice a conventional single-core, step-index, single-mode fibre to the central core of the fabricated MCF and to measure the transmission characteristics of the proposed fibre probe with a broadband light source and an optical spectrum analyser.

6 Acknowledgments

The authors would like to thank the Optacore team for supplying seven-core fibre to acquire knowledge about fluorescence probes.

7 References

1. K. V. Grattan, T. Sun, "Fiber optic sensor technology: an overview", Sensor and Actuators A: Physical,vol. 82, pp. 40-61,2000.
2. S. Begus, G. Beges, J. Dronvsek, D. Hudoklin, "A novel NIR laser-based sensor for measuring the surface moisture in polymers", Sensors and Actuators A: physical, vol. 221, pp. 53-59, 2015.
3. W. R. Seitz, "Chemical sensors based on fiber optics", Anal. Chem., vol. 56, pp. 16A-34A, 1984.
4. M. L. Myrik, S. M. Angel and R. Desidero,"Comparison of some fiber optic configurations for measurements of fluorescence and Raman scattering", Appl. Optics, vol. 29, no. 9, pp. 1333-1343, 1990.
5. A. H. Uddin, P. A. E. Piunno, R. H. E Hudson, M. J. Damha and U. J. Krull, "A fiber optic biosensor for fluorimetric detection of triple-helical DNA", Nucleic Acids Research, vol. 25, no. 20, pp. 4139–4146, 1997.
6. M. C. Yappert, S. Lai, and D. Borchmanj, "Age Dependence and Distribution of Green and Blue Fluorophores in Human Lens Homogenates", Invest. Opthalmol. Vis. Sci, vol. 33, no. 13, pp. 3555-3560, 1992.
7. L. A. Saari, W. R. Seitz, "pH Sensor Based on Immobilized Fluoresceinamine", Anal. Chem., vol. 54, pp. 821-823, 1982.
8. G.F. Kirkbright, R. Narrayanaswamy, N. Welti, "Fibre-optic pH probe based on the use of an immobilised colorimetric indicator", Analyst, vol. 109, pp. 1025-1028, 1984.
9. G. K. Bhowmic, N. Gautam, L.M. Gantayet, "Design optimization of fiber optic probes for remote fluorescence spectroscopy", Optics Communications. 282:2676-2684, 2009.
10. A. Samir, B. Batagelj, "A multicore fibre probe for fluorescence spectroscopy", Proceedings, 52nd International Conference on Microelectronics, Devices and Materials, September, Ankaran, Slovenia, MIDEM - Society for Microelectronics, Electronic Components and Materials 2016.
11. J.R. Guzmán-Sepúlveda, R. Guzmán-Cabrera, M. Torres-Cisneros, J.J. Sánchez-Mondragón, D.A. May-Arrioja, "A highly sensitive fiber optic sensor based on two-core fiber for refractive index measurement", Sensors vol. 13, 14200–14213, 2013.
12. X. Liu, S. Chandrasekhar, X. Chen, P.J. Winzer, Y. Pan, T.F. Taunay, B. Zhu, M. Fishteyn, M.F. Yan, J.M. Fini, E.M. Monberg, and F.V.Dimarcello ,"1.12–Tb/s 32–QAM–OFDM superchannel with 8.6–b/s/Hz intrachannel spectral efficiency and space–division multiplexed transmission with 60–b/s/Hz aggregate spectral efficiency", Opt. Express, vol. 19, pp. B958–B964, 2011.
13. I. Gasulla and J. Capmany, "Microwave photonics applications of multicore fibers", IEEE Photonics J., vol. 4, pp. 877–888, 2012.
14. B.M. Shalaby, V. Kermene, D. Pagnoux, A. Desfarges-Berthelemot, and A. Barthélémy, "Phase–locked supermode emissions from a dual multicore fibre laser", Appl. Phys. B, vol. 105, pp. 213–217, 2011.
15. Y. Huo, P. K. Cheo, and G. King, "Fundamental mode operation of a 19-core phase-locked Yb-doped fiber amplifier", Opt. Express, vol. 12, , pp. 6230–6239, 2004.
16. X. Li, B. Sun and Y. Yu, "Ultra-wide bandwidth wavelength selective couplers based on the all

solid multi-core Ge-doped fibre", Opto–Electronics Review, vol. 22, pp. 166–170, 2014.
17. M. Kovačič, J. Krč, B. Lipovšek and M. Topič, Modelling of diffraction grating based optical filters for fluorescence detection of biomolecules, Biomedical Optics Express, vol. 5, pp. 2285-2300, 2014.
18. P. R. Stoddart and D. J. White, "Optical fibre SERS sensors", Anal. Bioanal. Chem., vol. 394, pp. 1761–1774, 2009.
19. S. Dochow, I. Latka, M. Becker, R. Spittel, J. Kobelke, K. Schuster, A. Graf, S. Brückner, S. Unger, M. Rothhardt, B. Dietzek, C. Krafft, and J. Popp, "Multicore fiber with integrated fiber Bragg grating for background-free Raman sensing", Opt. Express, vol. 20, pp. 20156-20169, 2012.
20. M. Oto, "Resistivity for deep-UV laser irradiation in fluorine doped silica glass fiber", Proc. SPIE 6586, Damage to VUV, EUV, and X-ray Optics, vol. 6586, 2007.
21. A. S. Sudbo, "Film mode matching: a versatile numerical method for vector mode field calculations in dielectric waveguides. Pure", Appl. Opt. vol. 2, pp. 211-233, 1993.
22. S. T. Peng, and A. A. Oliner, "Guidance and leakage properties of a class of open dielectric waveguides: Part I mathematical formulations", IEEE-MTT vol. 29, pp. 843-855, 1981.
23. D. F. G. Gallagher, T.P. Felici, "Eigenmode Expansion Methods for Simulation of Optical Propagation in Photonics - Pros and Cons", Proceedings of SPIE, Vol 4987, pp. 69-82, 2003.
24. J. Hudgings, L. Molter, and M. Dutta, "Design and modeling of passive optical switches and power dividers using non-planar coupled fiber arrays," IEEE J. Quantum Electron. 36(12), 1438–1444 (2000).
25. Y. C. Meng, Q. Z. Guo, W. H. Tan, and Z. M. Huang, "Analytical solutions of coupled-mode equations for multiwaveguide systems, obtained by use of Chebyshev and generalized Chebyshev polynomials," J. Opt. Soc. Am. A 21(8), 1518–1528 (2004).
26. N. Kishi and E. Yamashita, "A simple coupled-mode analysis method for multiple-core optical fiber and coupled dielectric waveguide structures," IEEE Trans. Microwave Theory Tech. 36(12), 1861–1868 (1988).
27. J. Zhou, "Analytical formulation of super-modes inside multi-core fibers with circularly distributed cores", OPTICS EXPRESS, Vol 22, pp. 673-688, 2014.
28. C. Jollivet, A. Mafi, D. Flamm, M. Duparré, K. Schuster, S. Grimm, and A.Schülzgen, "Mode-resolved gain analysis and lasing in multi-supermode multi-core fiber laser", OPTICS EXPRESS, Vol 22, pp. 30377-30386, 2014.

Arrived: 03. 03. 2017
Accepted: 10. 04. 2017