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Finite element modeling of coupling characteristics of directional coupler for multiplexer and de-multiplexer application

Finite element modeling of coupling characteristics of directional coupler for multiplexer and de-multiplexer application

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Abstract. Numerical simulation of directional coupler that is based on the finite element method was conducted using the COMSOL Multiphysics software. The distributions of electric field and power flow of light propagates in two cores of directional coupler were analyzed. The results showed the dependencies of coupling length and maximum transfer power between cores on the cores separation and the wavelength, the characteristic of a subwavelength directional coupler can be used for photonic integrated circuits. Asymmetric directional coupler was also designed by changing in the device dimension, as the core width. The variation of coupling length with the core width were analysed. It was found that the power switching between cores is reduced when introducing a small difference in the one core width of directional coupler, followed by increased coupling length. At the same time, the coupling length can be decreased efficiently by increasing the difference in one core width; therefore, a directional coupler with large core width is more convenient to reduce the power switching between cores than the smaller core width. This study is useful for determining the coupling characteristics between the cores that may be used as a platform for future photonic integrated circuits in optical communication systems.

1. Introduction

The optical waveguide coupler is considered one of the most important components of integrated optics; it is used to control the refractive index by changing from one waveguide to another, in which the optical power is exchanged between the two cores; this leads to weak overlap of the evanescent electric fields between two waveguides [1], then the light will propagate in both independent waveguides and the coupling will occur between them, during which the light switching the back and forth over the coupling length can be observed [1, 3]. Currently, many optical devices can be fabricated using bulk material, by employing direct femtosecond laser writing [4]. An advanced optical network needs a variety of implemented functions, such as switches, power splitters, Mach-Zehnder interferometer and wavelength division multiplexing [4-6]. Recently, a number of studies were conducted on directional coupler theory and practical trends, such as the use of silica glass as a promising material for optical switching [7, 8], with such optical properties as good stability, loss-loss and efficient directional couplers operating in all telecom wavelengths [9, 10]. In general, any effects resulting from a change in the core separation between the two cores or a change in the core diameter are indeed equivalent to the change in the refractive index. The analysis of the behaviour of supermodes in the two cores changes, and the structure consisting of two cores supports two orthogonally polarized supermodes that may either be symmetric (even mode) having the same phase or asymmetric (odd mode) having a different phase. Every single core possesses exactly two orthogonally polarized supermodes that are similar to the fundamental modes of the single-core [11].

The change in the core separation between the coupled cores affects the coupling length; a decrease in the core separation between the coupled cores produces a large strength of coupling between the coupled cores and thus an increase in the coupling length. The gradual increase in the core separation between the coupled cores leads to a decrease, or perhaps suppression of the coupling strength between the coupled cores and thus decreases the coupling length or may be neglected. This result gives us the possibly for designing short or long coupling lengths of a two-core PCF coupler to decrease or increase of the rate of data transmitted in close or in the far distance telecommunication [12]. A simple change in the dimensions of the directional coupler is made, if a coupler consisting of two non-identical cores is used; in this way, the coupler can depend on mode coupling. This type of mode coupling has potential applications in Mode Division Multiplexing (MDM) for communication systems as long as it can increase the capacity of a channel [13-18], or it may lead to new concepts of multicore devices [11]. It was also found that the coupling properties are greatly affected depending on the amount of the change in core diameter and increasing the number of cores coupled inside the structure; hence the coupling efficiency between coupled cores is affected. As a result, the cores become decoupled, and the propagation of light in each core is independent of the other inside the structure; this gives us a novel characteristic of multiplexing-demultiplexing applications [19-21].

In this paper, a 3D waveguide directional coupler with different cores separation by COMSOL Multiphysics software was designed to analyse the coupling properties between two cores of the coupler. The dependencies of coupling length and maximum transfer power between cores on cores separation cores and the wavelength were found. In addition, asymmetric directional coupler was designed, the variation of directional coupler dimensions will introduce mismatching between cores, even if the effective refractive indices of two cores were equal and these effects on the coupling properties between them.

2. Design methodology, simulation results and discussion

2.1. Design methodology

A 3D waveguide directional coupler was simulated, using the COMSOL Multiphysics software dependence the FEM method to evaluate the coupling properties and switching of the light between cores of the directional coupler. The structural parameters of the directional coupler designed for silica material are the waveguide height (12 μm); waveguide width (18 μm), the waveguide length (2.1 mm), cores width (3 μm), core separation d is (2 μm), as shown in Figure 1. The refractive index of the core silica material $n_{co} = 1.45$ is slightly larger than the refractive index of the cladding material, $n_{clad} = 1.4$, modeled to the light guiding by total internal reflection mechanism (MTIR) between the core and the cladding region. Supermode analysis of three-core PCF by FEM directly solves the Maxwell equations to obtain an approximate value of the effective refractive indices of the modes. According to the supermode theory that relies on the mode coupling, there are four modes with different propagation constants either two modes are even and have the same phase or two modes are odd and have phase differences as π in both x- and y-polarization fields. Knowing the difference in the effective refractive indices between even and odd modes, and the wavelength λ that is used, the coupling length (L_c) can be directly calculated from the equation (1) as [11, 19-22]:

$$L_c = \frac{\pi}{\beta_{even} - \beta_{odd}} = \frac{\lambda}{2(n_{evem} - n_{odd})} \quad (1)$$

Where β_{even} and β_{odd} are represented the propagation constants of even and odd modes, and the refractive indices that correspond to it are (n_{even} and n_{odd}) L_c, which defines as a single power exchanged between two cores, resulting in the weak overlap of the adjacent electric field of two cores.

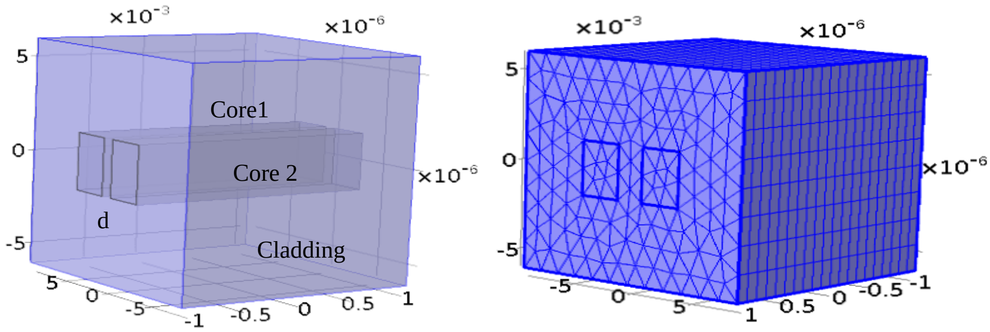

Figure 1. Simulated the geometry of 3D waveguide directional coupler using COMSOL Multiphysics depends FEM method, Directional coupler consists of the two cores with core separation is d (µm) and the surrounding cladding. The design is characterized by the structure parameters for silica material, such as the waveguide height 12 µm, width 18 µm, the length (2.2 mm), cores width (3 µm) and core separation (d) is 2 µm from (left). Mesh triangular finite element (right).

2.2. Simulation results and discussion

Figures 2 and 3 present the numerical results showing 2D and 3D Slice and Contour of distribution of the electric field norm E (V/m) for both wavelengths 1.55 µm (from up) and 1.31 µm (from down). The results of numerical simulation indicated that the power transmitted between two cores is maximum about (99%) of the power coupled with short coupling lengths 276.78 µm and 385.29 µm for both wavelengths 1.55 µm and 1.31 µm at small core separation 2 µm when the laser light is launched to one of two cores. Figure 3 shows the changes in the coupling length; due t a change in the separation distance to 2.5 µm or 3 µm, the coupling lengths increased to 861.1 µm and 1637 µm or 2583 µm and 6550 µm for wavelengths 1.55 µm and 1.31 µm, as in Table 1. The results showed that the coupling lengths at the wavelength 1.55 µm are less than 1.31 µm. Besides, the strength of coupling between cores reduces dramatically at a core separation 3 µm of each wavelength compared to 2 µm which is stronger as a result increase of overlap the evanescent fields between them. Thus, transmission loss and coupling efficient of directional coupler that operates in the telecom wavelength 1.55 µm are greater than at 1.31 µm and with low-loss and high- quality single-mode.

Table 1. The results of changing the coupling length with core.

Core separation (µm)	Coupling length at the wavelength (1.55 µm)	Coupling length at the wavelength (1.31 µm)
2	276.78	385.29
2.5	861.1	2583
3	1637	6550

The numerical results in Figure 4 showed that the difference in the refractive index is increased at the small core separation and begins to gradually decrease at large core separation for different wavelengths. On the other hand, the difference in the refractive index between even and odd modes is smaller at the short wavelength than at the longer wavelength. While changing the coupling length as a function of the core separation, the numerical results showed that the coupling length increases with an increase in the core separation; this is because the difference between the effective refractive index of the even and odd modes is lower and vice versa at the small core separation.

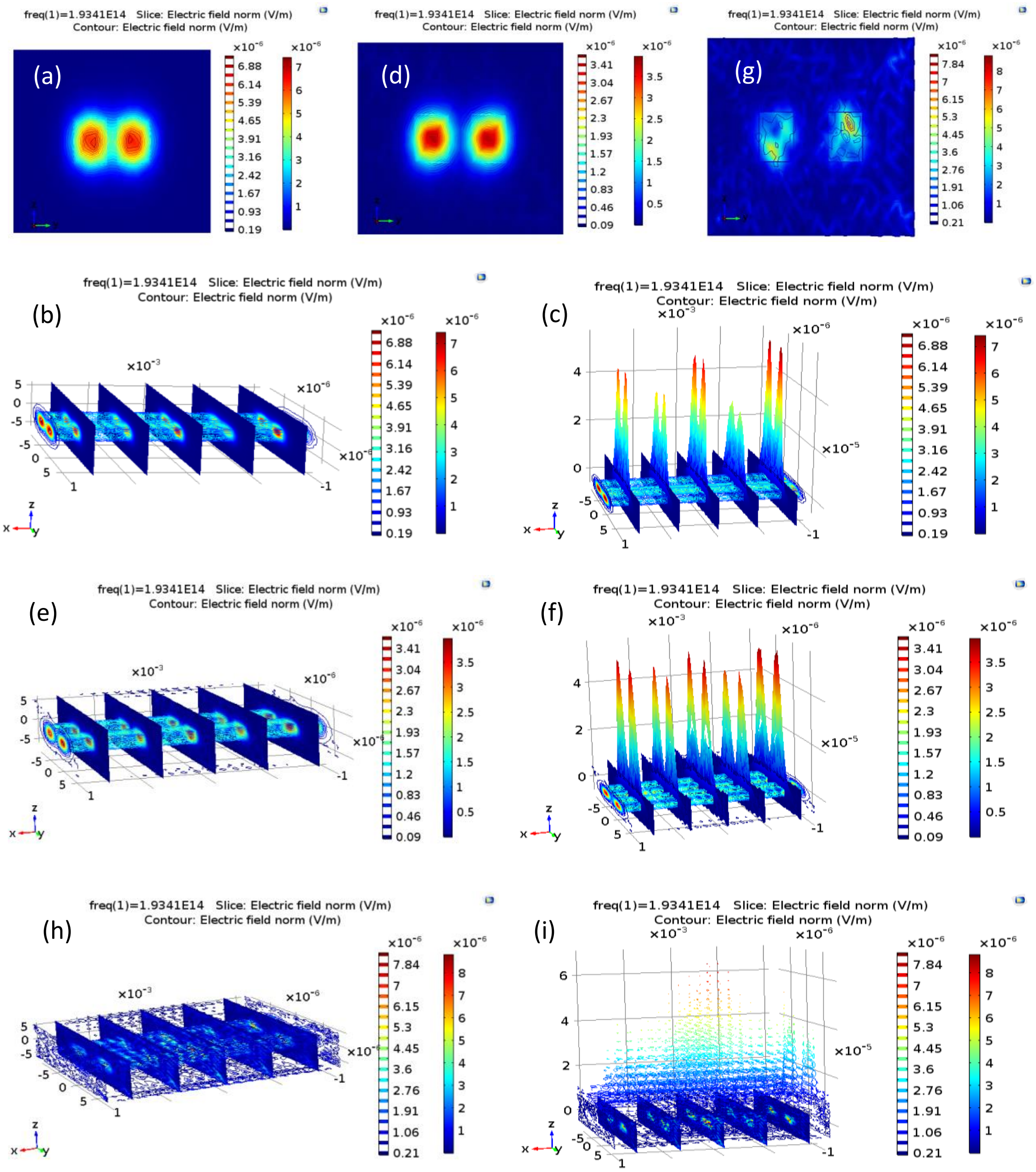

Figure 2. Cross–section of a two–core directional coupler for even supermodes in two dimensions (a, d, g), and in three dimensions (b, e, h); the electric field norm (V/m) is represented in the Slice distribution & Contour scale. In (c, f, i), the electric field intensity represented in the Slice-Deformation distribution scale & Contour scale, shown from up to down, indicated that the electric field intensity is increased from blue to red. All this results at the wavelength 1.55 μm for different separation distances between cores, such as 2 μm, 2.5 μm and 3 μm.

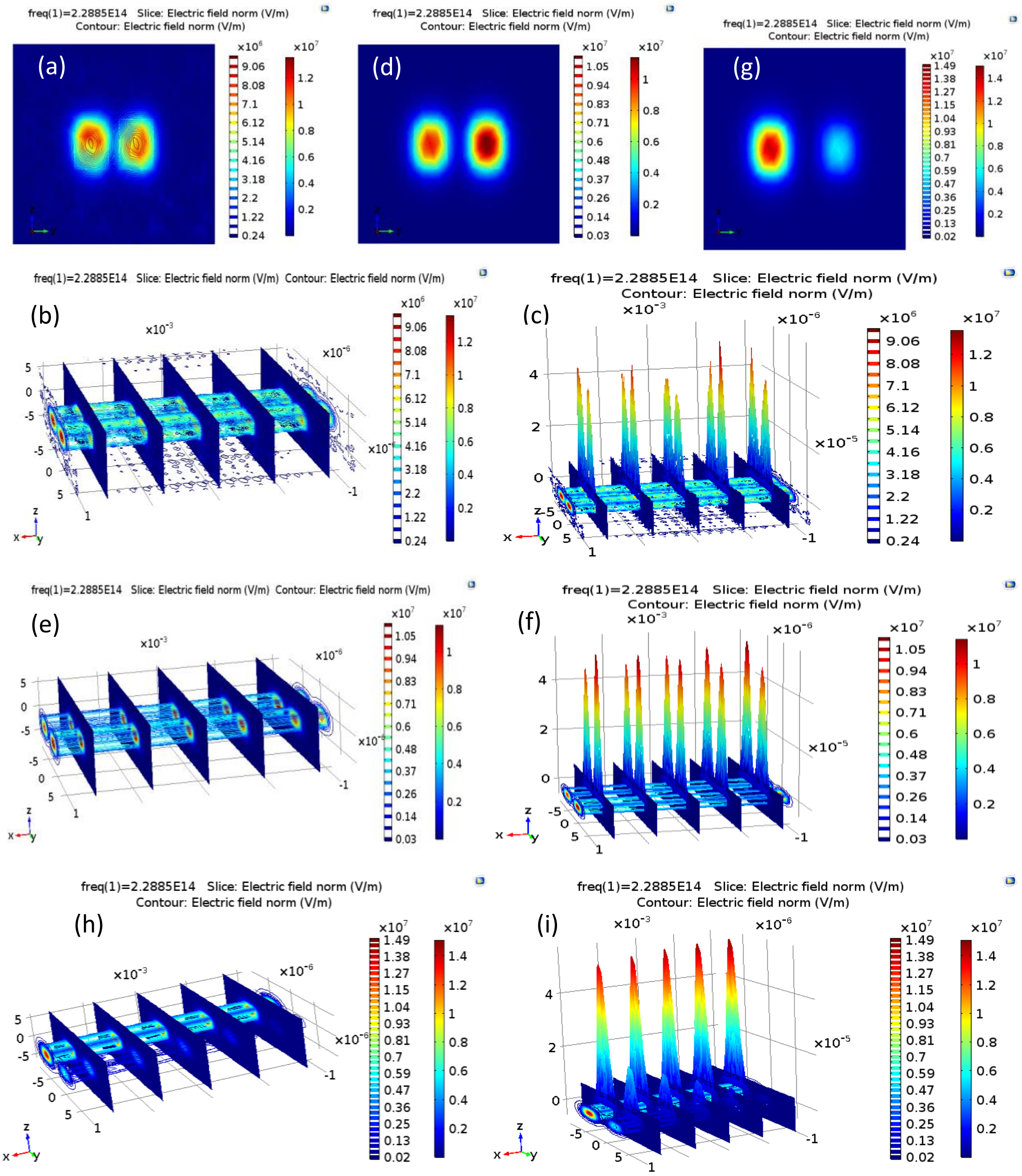

Figure 3. Cross–section of a two–core directional coupler for even supermodes in two dimensions (a, d, g), and in three dimensions (b, e, h); the electric field norm (V/m) is represented in the Slice distribution & Contour scale. In (c, f, i), the electric field intensity represented in the Slice-Deformation distribution scale & Contour scale, shown from up to down, indicated that the electric field intensity is increased from blue to red. All this results at the wavelength 1.31 µm for different separation distances between cores, such as 2 µm, 2.5 µm and 3 µm.

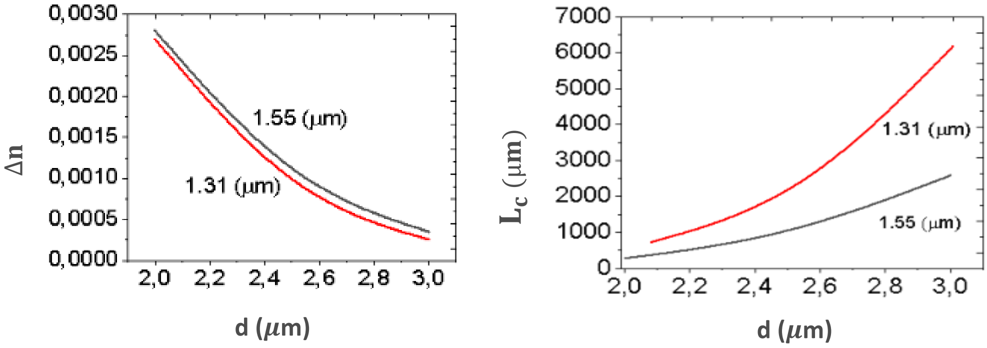

Figure 4. The difference in the effective refractive index of even and odd modes of couplers (left), and the coupling length (right) as a function core separation d (2 µm, 2.5 µm and 3 µm) and with different wavelengths 1.55 µm and 1.31 µm.

2.3. Simulation results and discussion

Coupling length of any directional coupler is considered an important parameter to optimize the size of the device. Therefore, an asymmetric directional coupler was designed by changing one core width of two cores using the same parameters as previous geometry with a fixed core separation as 3.4µm, since the coupling between cores related to the effective indices; therefore, such directional coupler was mismatching, the complete coupling between the cores cannot realized. The numerical results showed the change in the coupling and switching properties between cores of the directional coupler, as shown in Figure 5; effective indices as well as slice and contour electric field distributions of the directional coupler at the telecom wavelength 1.55µm, as shown in Figure 5 (a-e) for different core widths. The variation between the refractive index, difference between modes (Δn) and the core width, the coupling length with core width was also varied, as shown in Figure 6 and Table 2. The effective index difference was 0.002, 0.0043, 0.0097 and 0.0128, respectively, their coupling lengths were as follows: 387.5 µm, 180.23 µm, 79.89 µm and 60.546 µm at the core widths of 2.8 µm, 2.6 µm, 2,2 µm and 2 µm at the wavelength 1.55 µm. It was also found that the electric field did completely exist in the core with decreased width, while the electric field existed in the other core with fixed width. This shows that coupling and switching power between the two cores should be avoided.

Table 2. The results of changing the coupling length with core separation.

Core width (µm)	The effective index difference at the wavelength (1.55 µm)	Coupling length at the wavelength (1.55 µm)
2.8	0.002	387.5
2.6	0.0043	180.23
2.2	0.00097	79.89
2	0.0128	60.54

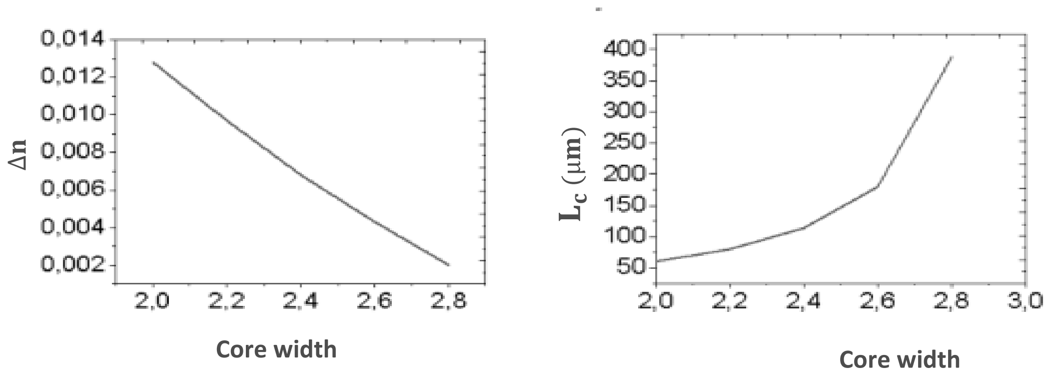

Figure 5. Variation the difference in the refractive between even and odd modes (right), and the coupling (left) as the core width of directional coupler at the wavelength 1.55 μm.

3. Conclusions

Numerically, using the COMSOL software to analyze the coupling properties of the directional coupler, many parameters limited the coupling properties between cores, such as cores separation and wavelength. The results showed that the coupling length increases along with core separation and reduced the wavelength. The simulation results enabled to fabricate a good directional coupler with short coupling lengths in (μm) with better coupling efficiency at the telecom wavelength 1.55 μm than at 1.31μmm with low-loss and high-quality single-mode. The devices with small coupling lengths are possibly used to develop compact devices for the mode-selective coupler. Asymmetric coupler structure has more advantages than the symmetric structure, if the switching power between cores has to be reduced. In addition, a coupler with large core width is more convenient for a single-mode waveguide than a small core width. All these results could be useful for multiplexing or demultiplexing applications in communication systems. Additionally, a coupler with large core width is more convenient for a single-mode waveguide than the small core width. All these results could be useful for multiplexing or demultiplexing applications in communication systems.

Acknowledgments

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