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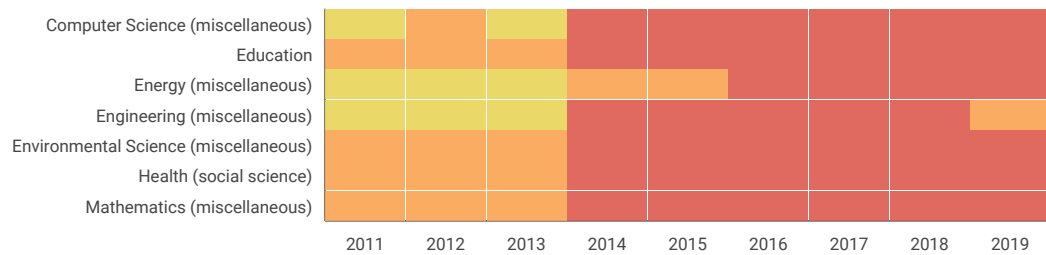
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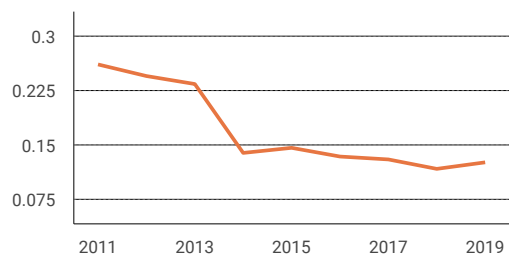
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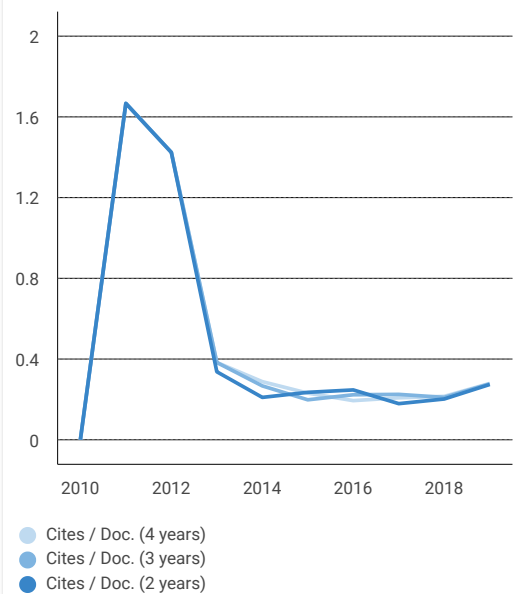
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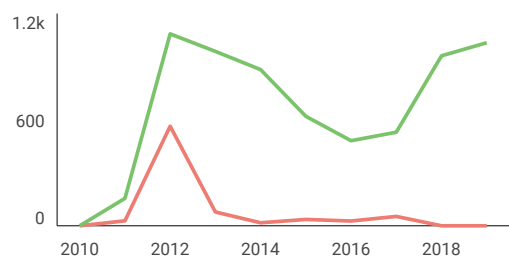
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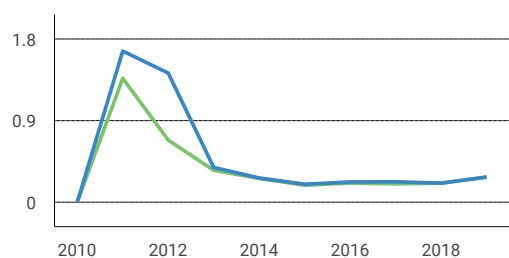
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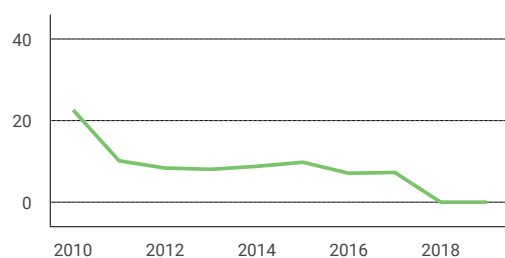
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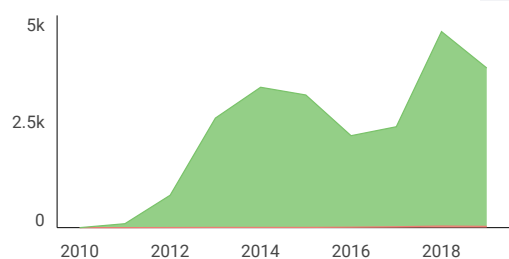
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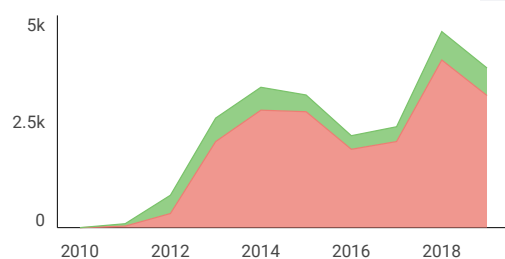
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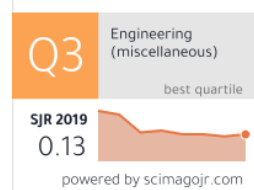
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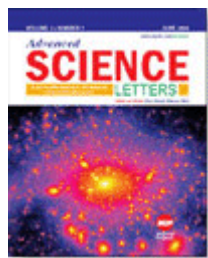
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Characteristics of Multi-Mode Interference Couplers by the Method of Lines

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Authors: Syahriar, Ary; Adam, Helmi; Djamal, Jusman Syafii; Lubis, H. Ahmad; Saleh, Randy Rahmat**Source:** Advanced Science Letters, Volume 23, Number 4, April 2017, pp. 3700-3703(4)**Publisher:** American Scientific Publishers**DOI:** <https://doi.org/10.1166/asl.2017.9032>**Abstract**

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Suggestions

Multi-mode interference couplers (MMI) based on the self-imaging principle can produce large number of optical outputs, this feature open huge application for power divider optical splitters in passive optical networks. Most splitters used in optical network such as a directional coupler can divide power into two or more outputs, but it is technically hard to fabricate due to its wavelength independence and its strict length requirements. One of the solutions of this strict fabrication tolerance is by introducing a large core in the splitting region as to accommodate more modes and splitting outputs. In this paper we design 1×16 MMI coupler, with optimum parameters to make the size of the device is practically still small. Power splitting ratio can be achieved at some special position where the mode front has 16 powers splitting level. We have used the Methods of Line to solve Helmholtz Equation in MMI structures. Further absorbing boundary condition is also used to prevent back reflection from the edge of calculation windows so that the error in calculation can be minimized. The calculation shows that MMI couplers have better tolerance on wavelength variation compare to standard type of directional couplers.

Keywords: Method of Lines; Multimode Interference Coupler; Self Imaging**Document Type:** Research Article**Affiliations:** Electrical Engineering Department, Faculty of Science and Technology, University Al-Azhar, Indonesia

Publication date: 01 April 2017

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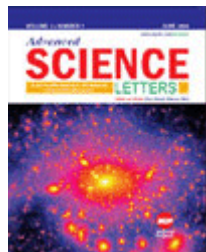
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Characteristics of Multi-Mode Interference Couplers by the Method of Lines

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Multi-mode interference couplers (MMI) based on the self-imaging principle can produce large number of optical outputs, this feature open huge application for power divider optical splitters in passive optical networks. Most splitters used in optical network such as a directional coupler can divide power into two or more outputs, but it is technically hard to fabricate due to its wavelength independence and its strict length requirements. One of the solutions of this strict fabrication tolerance is by introducing a large core in the splitting region as to accommodate more modes and splitting outputs. In this paper we design 1×16 MMI coupler, with optimum parameters to make the size of the device is practically still small. Power splitting ratio can be achieved at some special position where the mode front has 16 powers splitting level. We have used the Methods of Line to solve Helmholtz Equation in MMI structures. Further absorbing boundary condition is also used to prevent back reflection from the edge of calculation windows so that the error in calculation can be minimized. The calculation shows that MMI couplers have better tolerance on wavelength variation compare to standard type of directional couplers.

Keywords: Self imaging, multimode interference coupler, method of lines.

1. INTRODUCTION

Multimode Interference couplers devices have gained popularity due to their versatility for use in many optical circuits for example as power splitters, power combiners, and Mach–Zehnder optical switches. The basic structure of an MMI coupler requires a wide multimode waveguide section designed to support a large number of modes. In order for light to enter and exit from the wide multimode waveguide section, a number of narrow access waveguides are connected at the beginning and end of the multimode section, this known as input and output access waveguides. Devices configured as such are generally referred to as $M \times N$ MMI couplers, where M and N are the number of input and output waveguides respectively.

Operating principle of MMI is based on the self-imaging of multimode waveguides [4]. If a single-mode input field is launched to a wide waveguide that supports many modes, multiple images field are reproduced at certain distances along the propagation direction. We can stop wave propagation in the multimode section by choosing the length where the splitting power is similar to the requirement for certain number of output power. In the analyses the wavelength as the important characteristic for optical splitter are examined as well as the mechanism of power splitters. Because of the complexity on MMI structure, we use the Method of Lines (MoL) to solve wave propagation inside such structure.

The MoL has been proved to be a very useful tool for the analysis of general waveguide systems [2]. It is a semi analytical method, in which the wave equation is discretized as far as necessary in the transverse direction and solved analytically in the longitudinal direction, which results in less computational effort. An accurate result can be obtained since the MoL behaves in a stationary fashion and convergence is monotonic [3]. Discontinuous fields can be described accurately because the interface conditions are included in the calculation. Furthermore, the MoL is relatively easy to implement using computer numerical methods..

2. METHOD OF LINES

To analyze MMI by the method of lines, the region under analysis is broken into a large number of small elements Δx in the x direction as shown in Figure 1. As we see, the MMI structure consist three different sections in propagation directions. To analyze the devices each section in the propagation direction are divided into three regions where each region has its distinct refractive index distribution. The output of one section will become the input for the next section. For the analysis of a MMI waveguide, we start by assuming that the guide is weakly guiding. In addition, the medium is considered to be an isotropic, lossless dielectric. For a TE mode, assuming a monochromatic electromagnetic field with the angular frequency ω , the scalar wave equation for TE modes is given by [1],

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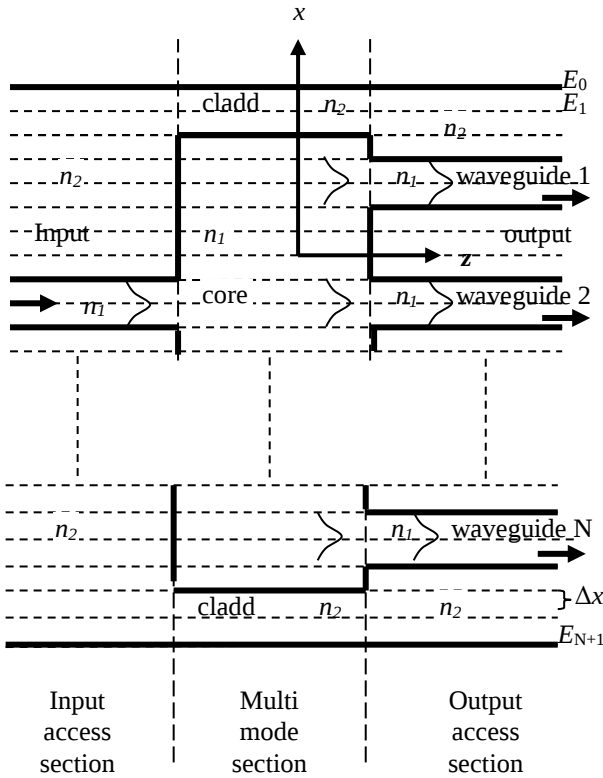


Figure 1. MMI discretization by the Method of Lines

$$\frac{d^2 \vec{E}_y}{dx^2} + \frac{d^2 \vec{E}_y}{dz^2} + k^2 \vec{E}_y = 0 \quad (1)$$

A central difference approximation is then assumed for the second derivative term $\frac{d^2 \vec{E}_y}{dx^2}$ so that:

$$\frac{d^2 \vec{E}_y}{dx^2} \cong \frac{E_{i+1} - 2E_i + E_{i-1}}{\Delta x^2} \quad (2)$$

Substitute Equation (2) into Equation (1):

$$\frac{d^2 \vec{E}_y}{dz^2} + \frac{E_{i+1} + 2E_i + E_{i-1}}{\Delta x^2} + k_o^2 n^2(x) \vec{E}_y = 0 \quad (3)$$

Equation (3) can be written in vector form as:

$$\frac{d^2 \vec{E}}{dz^2} + \vec{Q}^2 \vec{E} = 0 \quad (4)$$

Where $\vec{E}$ is transpose of column vector that consist $E(x)$ field in $x_1, x_2, \dots, x_n$ point.

And $\vec{Q}^2$ can be written as:

$$\vec{Q}^2 = \frac{1}{\Delta x^2} \begin{bmatrix} -2 & 1 & 0 & \dots & 0 \\ 1 & -2 & \dots & \dots & \dots \\ 0 & \dots & \dots & \dots & 0 \\ \dots & \dots & \dots & -2 & 1 \\ 0 & \dots & 0 & 1 & -2 \end{bmatrix}$$

$$+ k_o^2 \begin{bmatrix} n_{x1} & 0 & \dots & \dots & 0 \\ 0 & n_{x2} & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & 0 \\ 0 & \dots & \dots & 0 & n_{xN} \end{bmatrix} \quad (5)$$

Here, $n_{x1}, n_{x2}, \dots, n_{xN}$ is the refractive index distribution of MMI waveguides at different number of $x_1, x_2, \dots, x_n$ point.

$\vec{Q}^2$ consist of three diagonal matrix, to solve the equation we need to perform diagonalization of Equation (5) as:

$$\vec{\beta} = \vec{T} \vec{Q} \vec{T}^{-1} \quad (6)$$

Where $\vec{\beta}$ is diagonalization result from $\vec{Q}^2$ that consist of Eigen value, and $\vec{T}$ consist Eigen vector from $\vec{Q}^2$.

With that approach equation (6) can be rewritten as:

$$\frac{d^2 \vec{E}}{dz^2} + \vec{\beta}^2 \vec{E} = 0 \quad (7)$$

Equation (7) is wave equation that propagate in z direction. If we assume wave reflected to $-z$ direction is very small so it can be neglected, the solution becomes:

$$\vec{E} = e^{-i\vec{\beta}z} \quad (8)$$

To find solution of wave that propagate along z direction, we can use:

$$\vec{E} = \vec{T} e^{-i\vec{\beta}z} \vec{T}^{-1} \vec{E}_{inp} \quad (9)$$

If $\vec{\beta}$ varies, on the other hand, then the solution of Equation (9) must be divided into two or more separate solutions, for region 1 and 2 respectively. In section 1 the field is given by:

$$\vec{E}_1 = \vec{T}_1 e^{-i\vec{\beta}_1 z} \vec{T}_1^{-1} \vec{E}_{inp} \quad (10)$$

where $\vec{E}_{inp}$ is input field, while in the section 2 the field is given by:

$$\vec{E}_2 = \vec{T}_2 e^{-i\vec{\beta}_2 z} \vec{T}_2^{-1} \vec{E}_1 \quad (11)$$

In the section 3 the field is given by:

$$\vec{E}_3 = \vec{T}_3 e^{-i\vec{\beta}_3 z} \vec{T}_3^{-1} \vec{E}_2 \quad (12)$$

Here, the matrix $\vec{\beta}_3$ and $\vec{T}_3$ are analogous to $\vec{\beta}_2$ and $\vec{T}_2$ and $\vec{\beta}_1$ and $\vec{T}_1$ except that they are derived from the index distribution of each section. The full solution may be found by combining equation (10), (11) and (12) in the form $\vec{E}_2 = \vec{M}_3 \vec{M}_2 \vec{M}_1 \vec{E}_{inp}$, where $\vec{M}_1$, $\vec{M}_2$ and $\vec{M}_3$ are transfer matrices of the form $\vec{M}_i = \vec{T}_i \exp(-j\vec{\beta}_i z) \vec{T}_i^{-1}$. This method of solution can clearly be extended to treat geometries that vary continuously in the z -direction, by cascading a series of this solutions. One of the most important parameters associated with the waveguide is the fractional power that remains in the core at point z . This power is approximately given by the overlap integral:

$$P(z) = \left| \int_{-\infty}^{\infty} E(x,0)E(x,z)dx \right|^2 \quad (13)$$

where $E(x,0)$ is the input field and $E(x,z)$ is the field at point z .

1.1. ABSORBING BOUNDARY CONDITION

To calculate the radiation field, it is necessary to restrict the computational window. However an unfortunate choice of boundary barrier causes the radiation field at the edge of the computational window be reflected back into the calculation region, and hence give rise to a standing wave pattern that interferes with the final result. To overcome this difficulty, a slightly different absorbing boundary condition (ABC) is introduced. The most common method of defining an absorbing boundary condition is based on the factorization of the wave equation. To begin with, Equation (1) is rewritten as :

$$LE = (D_z^2 + D_x^2 + k_0^2 n^2)E = 0 \quad (14)$$

where :

$$D_x^2 \equiv \frac{\partial^2}{\partial x^2}, \quad D_z^2 \equiv \frac{\partial^2}{\partial z^2}$$

The operator L is then factored into inbound and outbound part L^+ and L^- as described in, so that,

$$LE = L^+ L^- E = 0 \quad (15)$$

where the terms L^+ and L^- are given by :

$$L^\pm = D_x \pm j\sqrt{\varepsilon}\sqrt{1+S^2}, \quad S^2 = \frac{D_z^2}{\varepsilon} \quad (16)$$

and : $\varepsilon = k_0^2 n^2$

If we want to prevent wave reflection at both edges of computational window, only outbound waves are allowed at that point. It can be shown that the field must then described by:

$$L^- E = 0 \quad (17a)$$

for the wave traveling in the -x direction and,

$$L^+ E = 0 \quad (17b)$$

for the wave traveling in the +x direction. Suitable absorbing boundary conditions will be obtained from these two equations. Unfortunately, the presence of the radical in Equation (14) prohibits the direct evaluation of Equation (15). An algebraic approximation of the radical then is needed to produce absorbing boundary conditions that can be implemented numerically with the MoL scheme. The radical can be approximated as:

$$\sqrt{1+S^2} \approx p_0 + p_2 S^2 \quad (16)$$

Here, the choice of the coefficients p_0 and p_2 is dependent on the method of interpolation. However, the values $p_0=1$ and $p_2=1/2$ are normally used.

3. NUMERICAL RESULTS

We have used silica on silicon based waveguide structure and parameters in all calculations. Here, the parameters of core refractive index is 1.468, cladding refractive index is 1.458, wavelength of 1.52 μm , core width in waveguide input section and output section is 3 μm , core width in the

multimode section is 80 μm . Figure 2 show the self-imaging phenomenon in multimode section. When single mode in a narrow input waveguide launched into the wider multimode section, the modes will break into many modes with different number of peak wave front power (bright point). These modes then propagate at different phase velocities, at some distances; the modes interfere coherently to form single or multiple mode power. This is happened periodically in multimode section.

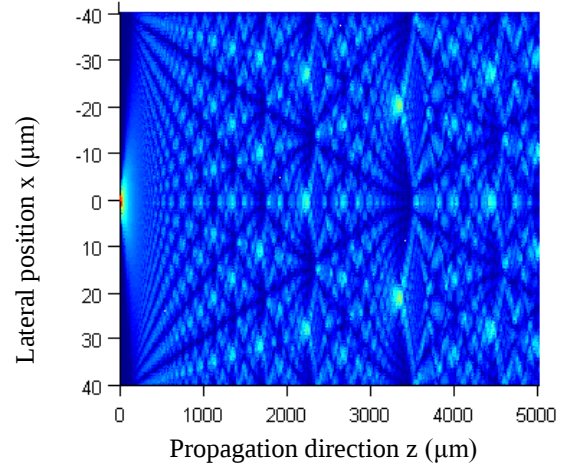


Figure 2. Wave propagation in multimode section

The maximum number of modes supported by the multimode section depends on the width of the multimode section. As the multimode section becomes wider, more modes are supported. The modes can divide into several output by stopping the propagation in multimode section in the length where single mode power number similar to the number of output we need, where all those output that is propagated into 16 single mode output channel. Figure 3 demonstrates the propagation of input power into multimode section. As the power entering the multimode section it is spread into multimode power with different number of peak wave front which specifies the number of power splitting. At a shorter distance the mode will be spread into large number of peak wave front with low power intensity; i.e. more output power, as it propagates further the wave front tends be smaller in number, i.e. less splitting output power. For 1x16 power splitter, the power split at propagation distance of $z=430 \mu\text{m}$. All 16 output power then is launched into 16 different parallel output waveguides. The result, we can make 1x16 coupler.

Figure 4 shows the wave propagation at the input and output power of 1x16 MMI coupler. The input power can be divided into equal 16 channel output power level at propagation distance of $z=430 \mu\text{m}$. Figure 5 demonstrates the power of each mode as it propagates in the multi-mode section which shows that at $z=430 \mu\text{m}$ the power converge and have similar power output level, this is the point where we choose to launched all power into separate 16 parallel waveguide to make it as 1x16 power splitters.

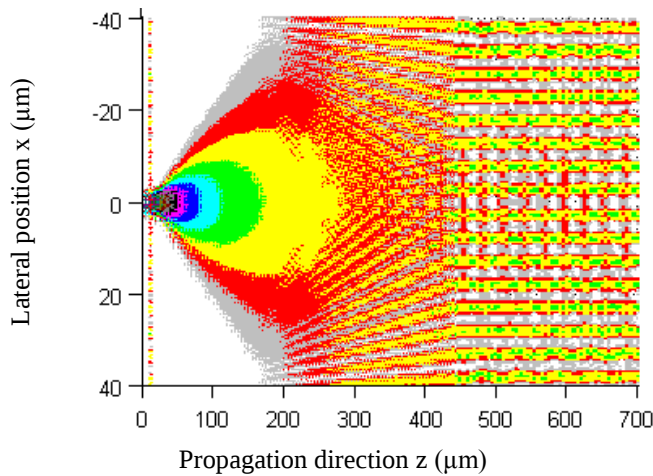


Figure 3. Wave propagation in 1x16 MMI coupler

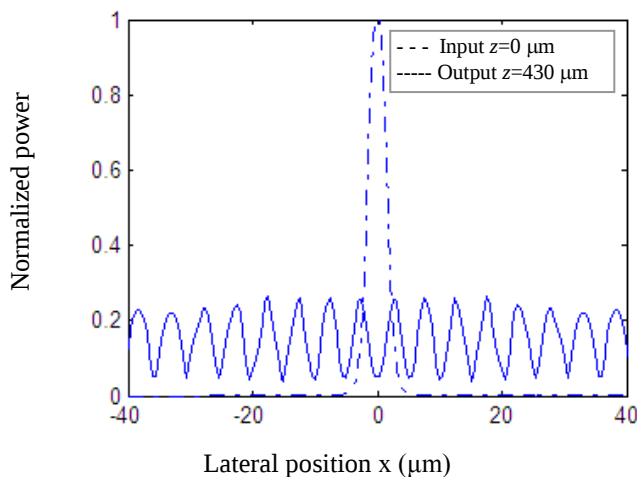


Figure 4. Input and output power distribution

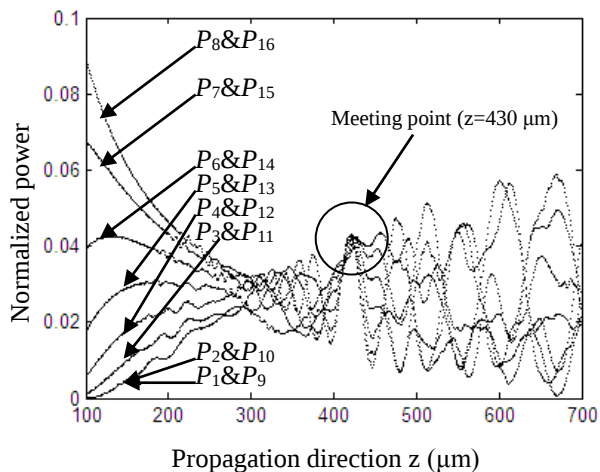
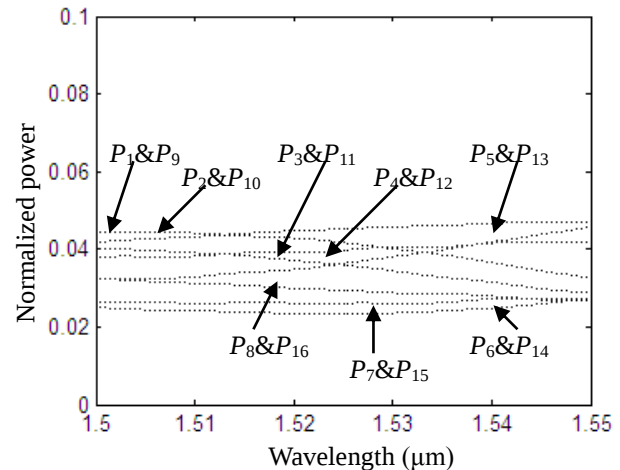


Figure 5. Power along propagation direction

Figure 6 demonstrates power at $z=430 \mu\text{m}$ as a function of wavelength. In this case we launch different wavelength starting from $\lambda=1.50\text{--}1.55 \mu\text{m}$ into MMI coupler, we can see clearly that the output power have relatively flat response to the wavelength change. This proves that MMI is independence of wavelength change. Meanwhile, in general directional couplers structure the devices are very heavy dependence on wavelength changes. This is the other advantage of MMI coupler.

Figure 6. Wavelength variation at $z=430 \mu\text{m}$

4. CONCLUSION

In this paper we have simulated the 1x16 MMI couplers using the method of lines as a new method to design MMI couplers. It shows that the MMI is a very versatile optical power divider that have relaxed fabrication tolerance and almost wavelength independence device. To obtain the shortest device, the MMI width should be chosen as narrow as possible to accommodate single mode and high confinement structure. Multimode interference coupler can produce many output, with the number of output is depend on length of propagation direction in multimode section. If the propagation stopped at near distance it will produce more output. We can make more output by increasing width of multimode section. The important characteristic for optical splitter is the wavelength dependence characteristics. In our simulation we have proved that the MMI coupler can produce flat power on multiple wavelength on each channel, it has better wavelength tolerance as compared with other splitter. Additionally the large number of output channel, it is the other advantage of MMI coupler.

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