Design and optimization of Optical power splitter based on Multimode Interference for 1.55-μm operation.

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Abstract – In this paper, we design and optimize 1X2, 1X4, 1X8, 1X16, and 1X32 optical power splitter based on Multimode Interference (MMI). A mathematical model is used to get accurate values of propagation constants and subsequently calculates the optimum value of coupler length of the MMI region, L_{MMI}. The results are predicted by the mathematical model, which gives the optimum values of the device properties such as excess loss and imbalance.

Keywords: Multimode interference (MMI), optical power splitter

1. Introduction

The challenge in optical access networking is to bring optical fibers as close to the end-users as possible and that is called Fiber to the home (FTTH). One way to realize this economically is to employ the passive double star (PDS) topology [I]. Therefore, it is necessary to use plenty of passive optical power splitters in the central office for distribution purposes. Some of the important characteristics of such splitter are low loss, compactness, compatibility with optical single mode fibers, uniform distribution of the output power on the output waveguides and a low cost. A power splitter 1×2 is usually a symmetric element, which equally divides power from a straight waveguide between two output waveguides. The simplest version of a power splitter is the Y-branch, which is easy to design and relatively insensitive to fabrication tolerances. Nevertheless, the curvature radii of the two branches, as well as the junction, must be carefully designed in order to avoid power losses. Also, if the two branches are separated by tilted straight waveguides, the tilt angle must be small, typically a few degrees [2].

A different version of a power splitter is the multimode interference element (MMI). This name comes from the multimodal character of the wide waveguide region where the power split takes place. The advantage of this design is the short length of the MMI compared to that of the Y-branch. Although the dimensions of the MMI are not critical, allowing wide tolerances, this element must be designed for a particular wavelength. The two power splitters, which have been described, are symmetric, and thus 50% of the input power was carried by each output waveguide. Nevertheless, asymmetric splitters can also be designed for specific purposes. In addition, it is possible to fabricate splitters with N output waveguides, and in that case the element is called a 1 × N splitter.

MMI devices are important components for photonic and optoelectronic integrated circuits due to their simple structure, low loss [3], large optical bandwidth and fabrication tolerance [4]. These structures provide power splitting or combining.

The organization of the paper is as follows. First, the theory and the principle of operation are described. The design of 1 X N power splitter based on MMI is presented. Then the geometrical design parameters as well as the number of input/output ports and MMI section are discussed. Finally, a brief conclusion is given.

2. Theory

Figure1 shows the top view of the MMI power splitter. The MMI power splitter consists of three parts: a single input waveguide of width w, a wide multimode waveguide section of width W_M, and a section of output waveguides of width w. Here W_M and L_{MMI} are the coupler width and the coupler length of the MMI region, respectively. To launch light into and receive light from that multimode waveguide, a number of single-mode waveguides are placed at its beginning and its end.

The basic principle that governs the reproduction of input images at the output waveguides is called the self-imaging principle [3]. Self-imaging is a property of multimode waveguides by which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide.

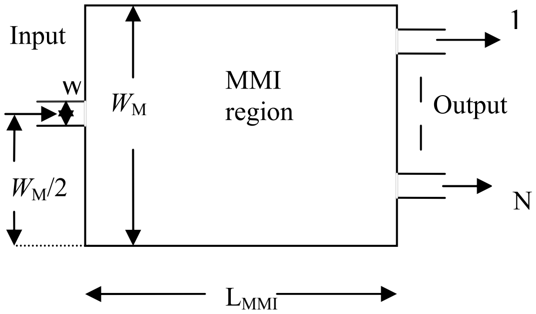


Figure 1: Top view of multimode interference power splitter (1 X N)

2.1 Self-imaging theory of MMI

For a strongly guided, step-index multimode waveguide, it can be assumed that the penetration depth of each transverse mode into the cladding is equal and negligible [5]. Thus, within the paraxial approximation, the distribution of propagation constant β_v is quadratic,

$$(\beta_0-\beta_v)\cong\frac{v(v+2)\pi}{3L_\pi} \tag{1}$$

where v is the mode number and L_π is the beat length of the two lowest-order modes [3]

$$L_\pi=\frac{\pi}{\beta_0-\beta_1}\approx\frac{4n_cW_M{}^2}{3\lambda_0} \tag{2}$$

n_c is the effective refractive index of the core. The β_v can be written as:

$$K_{vy}^2+\beta_v^2=k_o^2n_c^2 \tag{3}$$

with $$k_0=\frac{2\pi}{\lambda_0} \tag{4}$$

The approximated value of wavevector is formulated by [3] as:

$$K_{vy}\approx\frac{(v+1)\pi}{W_M} \tag{5}$$

The propagation constant can be expressed from (2), (3), and (5).

$$\beta_v=\sqrt{k_0^2n_c^2-\frac{(v+1)^2\pi^2}{W_M{}^2}}\approx k_0n_c-\frac{(v+1)^2\pi}{3L_\pi} \tag{6}$$

At the input to the multimode section, the field distribution of the input access waveguide can be expanded in the eigenmode of the multimode guide,

$$E(x,0)=\sum_{v=0}^{m-1}a_vE_v(x) \tag{7}$$

The field profile can be expressed from [2] as,

$$E_v(x)=\frac{\sin(K_{vy}x)}{\sin\left(\frac{K_{vy}W_M}{2}\right)} \tag{8}$$

So the excited modal amplitude a_v is then, in general determined by the overlap integral:

$$a_v=\frac{\int\sin(K_{vy}x)\cos\left(\frac{\pi x}{W_M}\right)dx}{\sqrt{\int\left(\sin\left(\frac{K_{vy}x}{W_M}\right)\right)^2dx}} \tag{9}$$

The field profile at a distance z can then write be written as superposition of all guided mode field distributions

$$E(x,z)=\sum_{v=0}^{m-1}a_vE_v(x)e^{j(\beta_0-\beta_v)z} \tag{10}$$

Equation (10) shows that the shortest N-fold self-imaging distance is

$$L_{MMI}=\frac{3L\pi}{4N} \tag{11}$$

from the input waveguide [3] for a 1 X N power splitter as shown in Figure 1.
Equation (6) is approximate equation to calculate the eigenmode of the propagation constant.

2.2 Numerical analysis

After solving Maxwell's equations and use the boundary condition of the symmetrical waveguide, the characteristic eigenvalue equation for TE modes is [5]:

$$\tan(K_{vy}W_M)=\frac{\sqrt{k_0^2(n_c^2-n_{cl}^2)-K_{vy}^2}}{K_{vy}}\quad\text{Even mode}$$

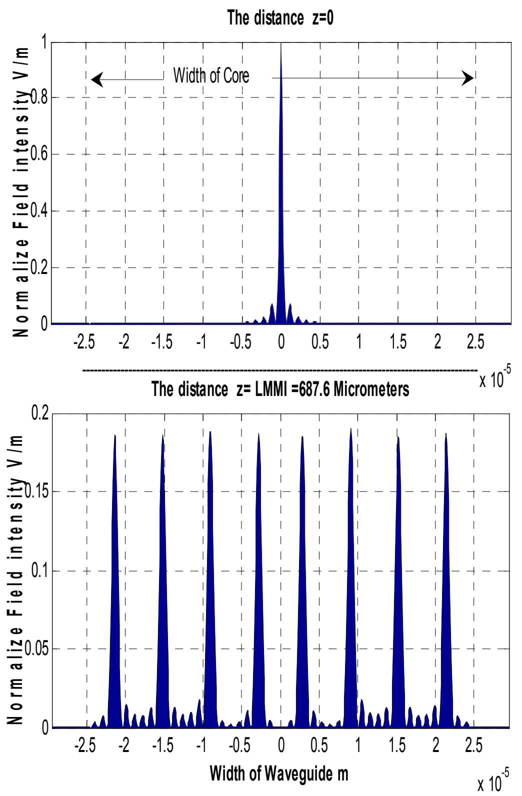
$$=\frac{-\sqrt{k_0^2(n_c^2-n_{cl}^2)-K_{vy}^2}}{K_{vy}}\quad\text{Odd mode} \tag{12}$$

Numerical analysis (Newton Raphson method) is used to solve (12). After that, K_{vy} values are replaced in equation (3) to find β_v values. Finally, equations (3), (7), (8), (9), and (10) are exploited.

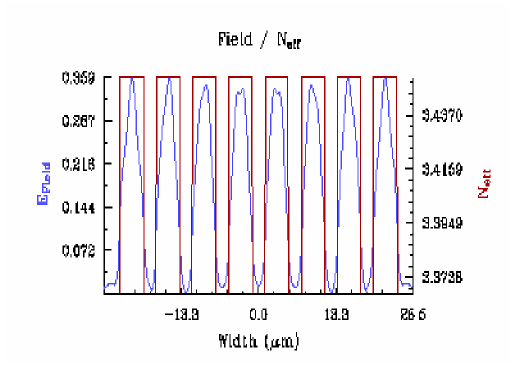
3. Results and analysis

During calculations and simulations in this work, the following parameters are kept constant. The operating wavelength, $\lambda=1.55\mu m$, and the refractive indices of the core and the cladding of the waveguides which use AlGaAs as the material [5].

n_c=3.454189744 (GaAs is doped by 5 % of Al) n_{cl}=3.36755329 (GaAs is doped by 20% of Al). The width of access input and output waveguide is $4\mu m$. Buried ridge is used as a channel waveguide. Figure 2 (a) and (b) show a simulation results for 1X8 power splitter based on mathematical model runs on Matlab and FD-BPM of the input and output fields distributions respectively. From Figure 2, it can be seen that the coupler length, L_{MMI} = 687.6 µm. The results of Figure 2 agree with these studies [3].



(a)



(b)

Figure 2: Field distribution at input and output of 1X8 optical power splitter based on MMI: (a) By mathematical module (b) By BPM-CAD

The MMI splitter is mainly characterized by an imbalance and an excess loss [1]. The power coupled to the i^{th} output waveguide is P_{oi} and the power coupled to the input waveguide is P_{in}. The performance of this power splitter is characterized by an excess loss and an imbalance in decibels, which are defined as [1]:

$$\text{Excess loss} = -10\log_{10}\left(\frac{\sum_{i=1}^{N} P_{oi}}{P_{in}}\right) \quad (13)$$

$$\text{Imbalance} = -10\log_{10}\left(\frac{P_{oi}^{\min}}{P_{oi}^{\max}}\right) \quad (14)$$

Here, $P_{oi}^{\min}$ and $P_{oi}^{\max}$ are the smallest and largest optical power at the output ports, respectively.

Figure 3 shows the optimum value of coupler length of 1X8 power splitter which occurs at the length ($689\mu m$), the lowest values of excess loss and imbalance are -0.0379384dB and -0.068854dB, respectively.

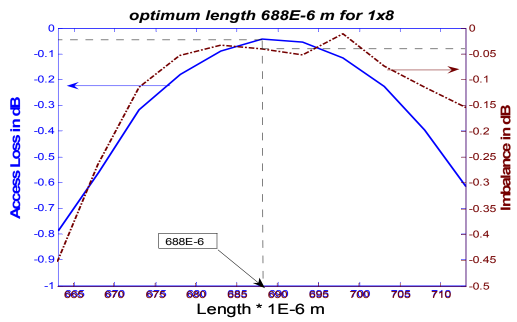


Figure 3: The length of MMI region vs. excess loss (solid line) and imbalance (dashed line). At L_{MMI}=688 μm the excess loss and imbalance are -0.03794dB and - 0.068854 dB respectively.

All results of 1X2, 1X4, 1X8, 1X16, and 1X32 power splitter based on MMI has been summarized as shown in Table 1. Comparison has been made with Soldano and Penning [3], our mathematical model, and Beam Propagation Method. When the number of output ports is small, the difference among the results in three cases is very small. The deviation of the result in the first case of the other will increase as increasing the number of output ports.

Table 1: Comparison among approximate equation (5), our mathematical model and the optimum length by FD-BPM-CAD

	In x Out	*1x2*	*1x4*	*1x8*	*1x16*	*1x32*
	Width (μm)	14.3	28.2	49.05	100.15	202.34
Soldano and Pennings' Approximation	*Length (μm)*	248	476	687.6	1380	2870
	Excess Loss(dB)	-0.03	-0.035	-0.048	-1.54	-1.52
	Imbalance (dB)	0	0.012	-0.05	-1.15	-2.703
	Deviation of length	0	0	-1.4 *μm*	-40 *μm*	-55 *μm*
Mathematical model by Numerical analysis	*Length (μm)*	248	477	689	1417	2930
	Excess Loss(dB)	-0.03	-0.035	-0.038	-0.073	-0.423
	Imbalance (dB)	0	-0.012	-0.069	-0.089	-0.36
	Deviation of length	0	0	0	-3 *μm*	+5 *μm*
Optimum length by FD-BPM	*Length (μm)*	248	477	689	1420	2925
	Excess Loss(dB)	-0.03	-0.035	-0.038	-0.057	-0.39
	Imbalance (dB)	0	-0.012	-0.069	-0.084	-0.39

The operation in MMI is more sensitive to length. Regarding the length of MMI section, it mainly depends on the lowest two propagation constants. They depend on the width of MMI section. The aims of approximate formula in the first case to calculate the propagation constant, this equation actually accumulate small deviation from the actual values of propagation constant. So the deviation of length increases as the number of modes increase which essentially depend on the width of MMI section. Mathematical model has used numerical analysis to get the propagation constant of the waveguide; the deviation of length by using this case is smaller than the length in the first case, as shown in Table 1.

4. Conclusion

We have modeled and simulated 1x2, 1x4, 1x8, 1x16, and 1x32 optical power splitters based on multimode interference (MMI) by using AlGaAs material which has strong guide property and operating at wavelength 1.55µm. The performance of the coupler was characterized by the modal propagation analysis. The lowest values of the excess loss and imbalance of the couplers are occurred at the optimum length. The properties of these devices (Excess loss and Imbalance) are sensitive to the dimension of the coupler. The modeling results agree well with simulation results.

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