Wideband Criterion for Multimode Interference Splitters

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***Abstract*—A wideband criterion for multimode interference (MMI) splitter is proposed. The basic principle is based on reducing the interference length difference and making it shorter than the spot size for constructive mode interference. Simulation results show the spectra of proposed MMI splitter is wide enough (1.26–1.70 μm) to cover the fiber communication band and the size of the splitter is more compact than that of the conventional MMI or Y-branch splitter.**

***Index Terms*—Multimode interference (MMI), power splitter, wideband.**

I. INTRODUCTION

OPTICAL networks are widely used in modern communication systems. The use of optical devices with good characteristics such as wide bandwidth, compact size, high fabrication tolerance, stable output, polarization independence, low-power loss, etc., is becoming more and more important. Devices based on multimode interference (MMI) are potential choices, because MMI devices have the advantage of low loss, polarization independence, compact size, and low fabrication cost. However, MMI devices are wavelength-sensitive. Variation of signal wavelength may have a significant influence on the performance of the device. To have a wideband MMI device is then of great interest for study.

In this work, a criterion for the design of wavelength-insensitive MMI splitter is proposed. Simulation results show the spectra of proposed MMI splitter is wide enough (1.26–1.70 μm) to cover the fiber communication band and the size of the proposed splitter is more compact than that of the conventional MMI or Y-branch splitter.

II. WIDEBAND CRITERION

From those reported previously [1]–[3], the coupling length L_{c} of curved MMI device can be approximated as

$$L_{\mathrm{c}} \cong \frac{4n_{\mathrm{g}}}{3\lambda} W_{\mathrm{e}}^2 \cdot \frac{1}{R} \tag{1}$$

where n_{g} is the waveguide index, λ is the signal wavelength, W_{e} is the effective width of interference region, and R is the reduction factor. Note that R is dependent on the structure of the interference region. For a linearly tapered MMI devices, R is equal to $1/(1 - d\ \Omega)$, where $d\Omega = 1 - W_1/W_0$, and W_0 and W_1 are the maximum and minimum width of the interference region, as shown in Fig. 1. For a conventional MMI device, $W_0 = W_1$, which corresponds to $d\Omega = 0$ or $R = 1$. The coupler length of MMI splitting is given by [1]

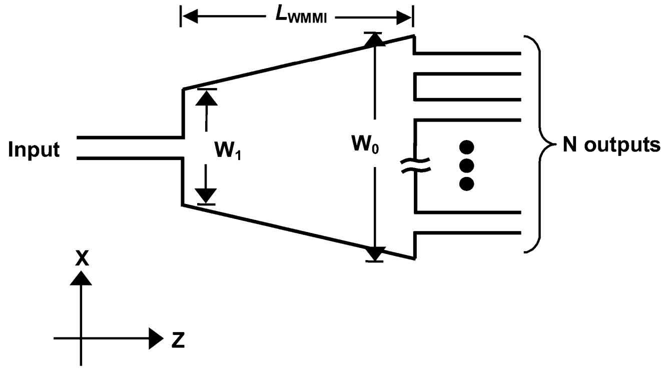

Fig. 1. Structure of proposed wideband MMI splitter.

$$L_{\mathrm{MMI}} = \frac{3}{4N} \cdot L_{\mathrm{c}} \tag{2}$$

where N is the number of output ports of the MMI splitter. When a conventional MMI splitter is to be operated at two wavelengths such as 1.31 and 1.55 μm, the spot size of an optical mode interference images ΔL_{spot} must be considered. For convenience, the spot size ΔL_{spot} of an output field distribution is defined as

$$\Delta L_{\mathrm{spot}} = |z_{\mathrm{F}} - z_{\mathrm{B}}| \tag{3}$$

where

$$|E(x_{\mathrm{M}}, z_{\mathrm{F}})|^2 = |E(x_{\mathrm{M}}, z_{\mathrm{B}})|^2 = 0.8|E(x_{\mathrm{M}}, z_{\mathrm{M}})|^2 \tag{4}$$

where $(x_{\mathrm{M}}, z_{\mathrm{M}})$ are the coordinates of a local maximum intensity, and $(x_{\mathrm{M}}, z_{\mathrm{F}})$ and $(x_{\mathrm{M}}, z_{\mathrm{B}})$ are the front and back coordinates in the propagation direction where the maximum intensity is down to 80%.

The basic idea for having an MMI splitter to operate within a wide wavelength band (i.e., less sensitive to wavelength) is to make the length difference ΔL_{MMI} shorter than the spot size ΔL_{spot} such that the optical modes at both wavelengths are overlapped within the same interference region. Therefore, the wideband criterion can be written as

$$\Delta L_{\mathrm{MMI}} \leq \Delta L_{\mathrm{spot}}. \tag{5}$$

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One possible approach to satisfy (5) is to reduce the length of interference region at the wavelengths such as 1.31 and 1.55 μm. From previous results, the linearly tapered MMI splitter has a shorter length, so it is chosen as the proposed wideband MMI splitter [2]. The length L_{WMMI} for operating between two signal wavelengths λ_1 and λ_2 $(\lambda_1 < \lambda_2)$ can be approximated as

$$L_{\mathrm{WMMI}} \cong \frac{\lambda_2}{\lambda_1 + \lambda_2} L_{\mathrm{MMI}}(\lambda_1) + \frac{\lambda_1}{\lambda_1 + \lambda_2} L_{\mathrm{MMI}}(\lambda_2). \quad (6)$$

The length difference of MMI device ΔL_{MMI} can then be written as

$$\Delta L_{\mathrm{MMI}} = L_{\mathrm{MMI}}(\lambda_1) - L_{\mathrm{MMI}}(\lambda_2) = \frac{n_g W_e^2}{RN} \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right). \quad (7)$$

From (5) and (7), the maximum value of W_e can be obtained as follows:

$$W_{\mathrm{e}} \leq \sqrt{R \cdot \frac{N}{n_{\mathrm{g}}} \cdot \left(\frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} \right) \cdot \Delta L_{\mathrm{spot}}} \quad (8)$$

and the maximum number of channels supported by the MMI splitter can be estimated to be

$$N_{\max} = \frac{W_{\mathrm{e}}}{(W_{\mathrm{g}} + d_{\mathrm{gap}})} \quad (9)$$

where W_{g} is the width of single-mode waveguide and d_{gap} is the gap of waveguide separation.

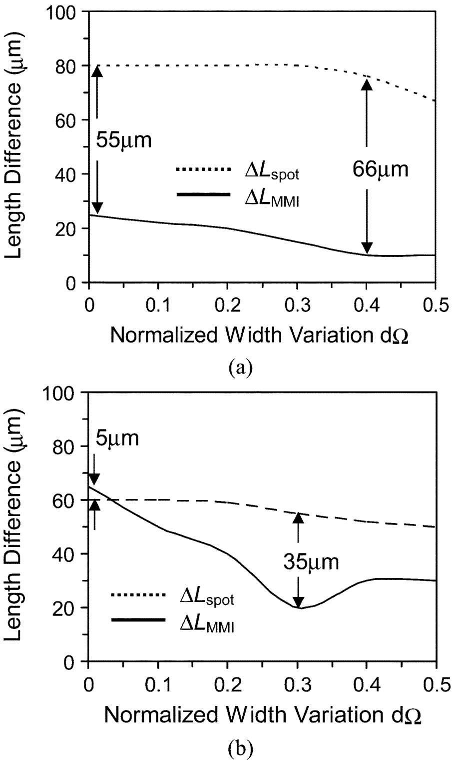
III. PERFORMANCE OPTIMIZATION

To optimize the wideband criterion by the beam propagation method (BPM), a single-mode waveguide of size 4×4 $\mu\mathrm{m}^2$, core index $n_{\mathrm{g}} = 1.472$, cladding index $n_{\mathrm{c}} = 1.45$ is considered. These device parameters are close to those of silica channel waveguides for commercial application. The values of W_0 are assumed 20 and 40 μm for the 1×2 and 1×4 splitter, respectively. Fig. 2 shows the values of ΔL_{spot} and ΔL_{MMI} for d Ω varying from 0 to 0.5. As can be seen from the figure, the wideband condition is satisfied for all $d\Omega$ in the range of interest except that $0 < d\Omega < 0.03$ in the case of 1×4 splitter. When the values of $d\Omega$ are 0.4 and 0.3, the differences between ΔL_{MMI} and ΔL_{spot} are the maximum for 1×2 and 1×4 splitter, respectively. The best wideband criterion is occurred when the difference between ΔL_{MMI} and ΔL_{spot} is the maximum. The average transmissions (defined as the average of normalized transmitted powers at 1.31 and 1.55 μm) are 0.96 and 0.89 for 1×2 and 1×4 proposed case, respectively, as shown in Fig. 3, which are good enough for practical application. Note that the conventional 1×4 MMI splitter does not satisfy the wideband condition, and therefore, can only operate at a very narrow wavelength band. Though the spot size is decreased as the MMI length gets shorter, the wideband condition is valid for $d\Omega$ in the range of interest $(0 < d\Omega < 0.5)$.

IV. BPM VERIFICATION OF SPECTRA RESULTS

To verify the wideband criterion for MMI splitters, the spectra results are simulated by BPM. Table I shows the calculated L_{WMMI} values of the proposed 1×2 and 1×4 splitter. Obviously, the proposed devices are more compact than the conventional ones. Fig. 4(a) and (b) shows the spectra of the proposed 1×2 and 1×4 wideband MMI splitter, respectively. As can be seen, for the 1×2 wideband MMI splitter, the 0.5-dB bandwidth is even beyond the common fiber communication wavelength band 1.9 μm. Thus, more than 77% improvement can be obtained. The bandwidth of proposed 1×4 splitter is about 66% wider than that of the conventional one.

Moreover, from the above results, the best parameters are $d\Omega = 0.4$ (or $R = 1.67$) and $d\Omega = 0.3 (R = 1.43)$ for 1×2 and 1×4 linearly tapered MMI splitters, respectively, and the corresponding values of ΔL_{spot} are about 80 and 60 μm, respectively. From (8), the maximum values of W_e are 39 and 44 μm for 1×2 and 1×4 linearly tapered MMI splitters, respectively.



(a)

(b)

Fig. 2. ΔL_{MMI} and ΔL_{spot} versus $d\Omega$ for the proposed MMI splitters. (a) 1×2. (b) 1×4.

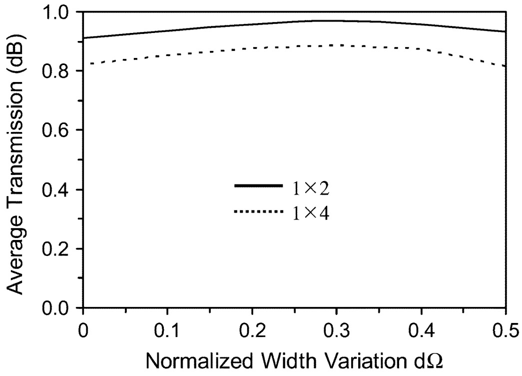
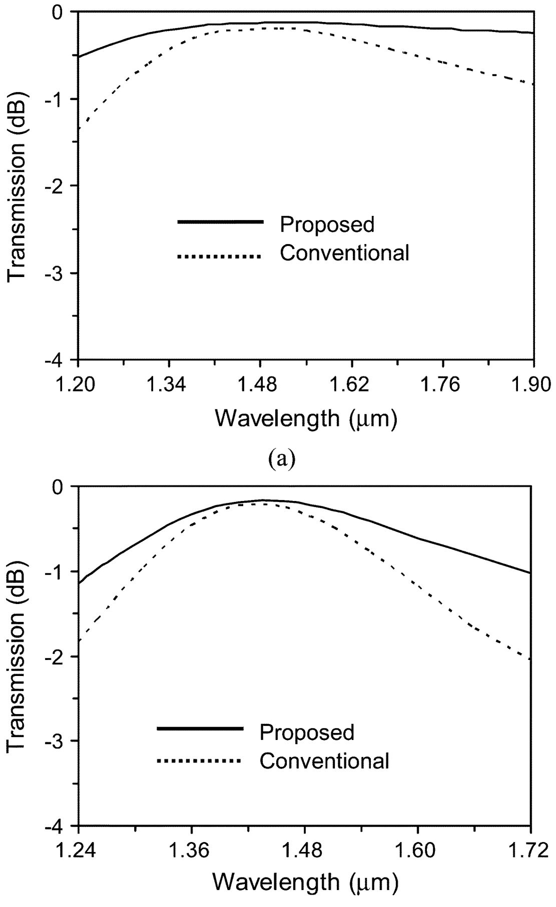


Fig. 3. Average transmission difference versus d Ω for the proposed MMI splitters.

TABLE I
COMPARISON OF L_{MMI} OF PROPOSED AND CONVENTIONAL MMI SPLITTERS

Splitter	Coupler Length					
	Proposed			Conventional		
	L_{MMI} (1.31)	L_{MMI} (1.55)	L_{WMMI}	L_{MMI} (1.31)	L_{MMI} (1.55)	L_{WMMI}
1×2	170	160	165	265	240	250
1×4	340	320	330	490	430	460

Unit: μm



(a)

(b)

Fig. 4. Spectra of the proposed wideband MMI splitters. (a) 1 × 2. (b) 1 × 4.

TABLE II
COMPARISON OF WAVELENGTH BANDWIDTH OF THE PROPOSED AND CONVENTIONAL MMI SPLITTERS

Splitters	Wavelength bandwidth (Wavelength range)		
	Proposed	Conventional	Bandwidth improvement
1×2	>700 (1204~1900)	394 (1326~1720)	>77%
1×4	455 (1256~1711)	274 (1305~1579)	~66%

Unit: nm

However, the values of W_e are only 30 and 37 μm for 1 × 2 and 1 × 4 rectangular MMI splitters, respectively. Table II shows the bandwidth and operation wavelength of the proposed and conventional MMI splitters by BPM simulation. The bandwidths of 1 × 2 and 1 × 4 linearly tapered cases are over 77% and about 66% wider than those of the rectangular ones. Thus, for the same W_e, MMI splitter with a tapered interference region designed by (5) is more suitable for wideband operation.

With the proposed wideband criterion, the bandwidth of a MMI splitter can be further improved by using a different tapered interference region. Wideband MMI splitters with more channels can also be designed. Details of the application are for future study.

V. CONCLUSION

A criterion for the design of MMI power splitters covering the wavelength band from 1.26 to 1.70 μm is presented. The criterion can be easily realized with a specially-designed linearly-tapered MMI splitter. Simulation results show that the 0.5-dB bandwidth is over 700 nm for the proposed two-channel MMI splitter and 1-dB bandwidth is about 455 nm for a four-channel one. The lengths of the proposed wideband MMI splitters can be greatly reduced. As the MMI splitters are insensitive within the band for fiber communication, they can be easily applied for the design of compact-sized wideband MMI splitters. Furthermore, as only the shape of the MMI region is considered, it can also be easily incorporated into complex integrated waveguide devices. Details of the application of the proposed wideband MMI splitters will be of great interest in the future.

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