Exponentially tapered multi-mode interference couplers

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Optical couplers are important components in photonic integrated circuits. The multi-mode interference (MMI) coupler is a good candidate because of its bandwidth, polarization properties, and manufacturing tolerances. A MMI coupler with the exponentially tapered multi-mode waveguide is proposed in order to reduce the scale of the MMI device. Compared with parabolically tapered structure which has been successfully used in the MMI devices, this structure can further reduce the length of devices. Simulation results by the beam propagation method for MMI couplers are given. The effectiveness of this structure for reducing MMI device length is proved.

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As an important element in integrated optics, 1 × 2 couplers are widely used as optical splitter and optical combiner. In recent years, multi-mode interference (MMI) couplers based on self-imaging effects have attracted more and more attention in the design of integrated optical circuits due to its advantages such as compactness, better manufacturing tolerances, insensitivity to polarization, and large bandwidth[1−4]. The main drawback of MMI technology is that couplers tend to be large if we are trying to obtain low loss and high accuracy. Recently, it was proposed that MMI couplers could be parabolically tapered to reduce the MMI scale[5,6]. Such tapered MMI couplers based on InP and silicon-on-insulator (SOI) waveguides have been realized[7−9]. In this letter we propose another tapered structure and simulate the performance of this kind of MMI devices by beam propagation method (BPM).

The MMI coupler is composed of a single-mode input waveguide, a multi-mode waveguide, and two single-mode output waveguides. The structure of the compact tapered 3-dB MMI coupler is illustrated in Fig. 1. The width is exponentially tapered according to

$$W(z) = W_{\rm i} + A\left[\exp\left(\frac{gz}{L_{\rm MMI}}\right) - 1\right], \tag{1}$$

$$A = (W_{\rm o} - W_{\rm i})/(\exp(g) - 1), \tag{2}$$

where z is the direction of propagation of the light, $L_{\rm MMI}$ is the length of the tapered MMI section, $W_{\rm i}$ is the width of the MMI section at $z = 0$ and $W_{\rm o}$ is that at $z = L_{\rm MMI}$, and g is a parameter associated with the shape of the profile. The input waveguide is located at the center of the start wall of the tapered MMI section, and the two output waveguides are located at $W_{\rm o}/4$ and $3W_{\rm o}/4$, respectively, on the end wall of the tapered MMI section. In order to improve the performance of the coupler, linearly tapered waveguides are used at the end wall of the MMI section.

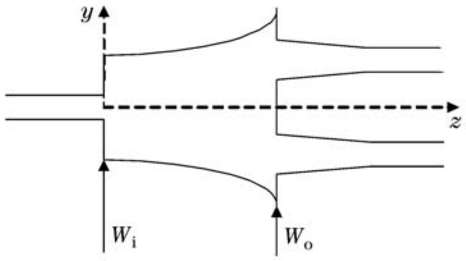

Fig. 1. Schematic of a 1 × 2 exponentially tapered 3-dB MMI coupler.

Assuming the multi-mode waveguide supports m lateral modes with mode orders $v = 0, 1, 2, \cdots, (m-1)$ at a free space wavelength λ, the effective index of the multi-mode waveguide section and the lateral confinement section is $n_{\rm r}$ and $n_{\rm c}$, respectively. According to the dispersion equation, the lateral wave number, k_{vy}, and the propagation constant β_v are related as follows[10]

$$k_{vy}^2 + \beta_v^2 = k_0^2 n_{\rm r}^2, \tag{3}$$

where $k_0 = 2\pi/\lambda$, $k_{vy} = (v+1)\pi/W_{\rm e}(z)$, and $W_{\rm e}(z)$ is the effective width of the MMI section,

$$W_{\rm e}(z) = W(z) + W_{\rm g}, \tag{4}$$

and the Goos-Hänchen shift $W_{\rm g}$ is determined by

$$W_{\rm g} = \left(\frac{\lambda}{\pi}\right)\left(\frac{n_{\rm c}}{n_{\rm r}}\right)^{2\sigma}\left(n_{\rm r}^2 - n_{\rm c}^2\right)^{-1/2}, \tag{5}$$

with $\sigma = 0$ for transverse electric (TE) mode and $\sigma = 1$ for transverse magnetic (TM) mode.

The propagation constants β_v can be deduced from Eq. (3) as

$$\beta_v \approx k_0 n_{\rm r} - \frac{(v+1)^2 \pi\lambda}{4n_{\rm r}W_{\rm e}^2(z)}. \tag{6}$$

Therefore, the phase change between the v order mode and the fundamental mode over the exponentially tapered waveguide can be given by

$$\Delta\phi = (\beta_0 - \beta_v)L_{\rm MMI} = \int_0^{L_{\rm MMI}}(\beta_0 - \beta_v){\rm d}z$$
$$= v(v+2)\frac{\pi\lambda}{4n_{\rm r}}\int_0^{L_{\rm MMI}}\frac{{\rm d}z}{W_{\rm e}^2(z)}. \tag{7}$$

Substituting Eqs. (1), (2), (4), and (5) into Eq. (6) yields

$$\beta_0 - \beta_v = \frac{v(v+2)\pi\lambda\gamma}{4n_r W_o^2}, \quad (8)$$

where

$$\gamma = \frac{W_o^2}{(W_g + W_i - A)^2} - \frac{W_o^2}{g(W_g + W_i - A)^2}\ln\left(\frac{W_g + W_o}{W_g + W_i}\right) - \frac{W_o^2(W_o - W_i)}{g(W_g + W_i - A)(W_g + W_o)(W_g + W_i)}. \quad (9)$$

The beat length L_π^e of the two lowest order modes is

$$L_\pi^e = \frac{\pi}{\beta_0 - \beta_1} = \frac{4n_r W_o^2}{3\gamma\lambda}. \quad (10)$$

For the parabolically tapered structure, the beat length of the two lowest order modes can be similarly obtained as[9]

$$L_\pi^p = \frac{\pi}{\beta_0 - \beta_1} = \frac{4n_r W_o^2}{3\alpha\lambda}, \quad (11)$$

where

$$\alpha = \frac{W_o^2}{2(W_g + W_i)(W_g + W_o)} + \frac{W_o^2 \tan^{-1}[(W_o - W_i)/(W_g + W_i)]^{1/2}}{2(W_o - W_i)^{1/2}(W_g + W_i)^{3/2}}. \quad (12)$$

For the structure shown in Fig. 1, the input single-mode waveguide is located at the center of the start wall of tapered MMI section, and only even-symmetric modes are excited in the tapered MMI section. Then two symmetric interference images can be formed, with a length of

$$L_{\mathrm{MMI}} = (3/8)\, L_\pi. \quad (13)$$

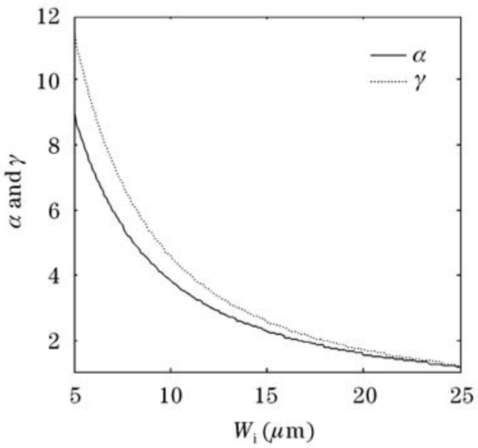

Fig. 2. γ and α versus the input width W_i.

Comparing Eqs. (10) and (11), we can see the difference of the beat length of the two lowest order modes between the parabolically and the exponentially tapered structures. The beat length has relationship with the parameters γ and α. Obviously, the larger the value of γ (or α) is, the shorter the length of the MMI section is. Figure 2 illustrates γ and α as functions of the width W_i for TE mode. In our calculation, the values of $n_r = 1.47$ and $n_c = 1.40$ are chosen, the width of the tapered MMI section at W_o, $z = L_{\mathrm{MMI}}$, is 24 μm, and $g = 5$. It can be seen from Fig. 2 that γ is larger than α in the variation range of W_i. Then for the MMI couplers with the same width at either the start wall or the end wall of the tapered MMI section, the length of MMI section with exponential taper is shorter than the length of that with parabolic taper. It is very favorable for the realization of ultra-compact MMI devices. So this exponentially tapered structure will be a good candidate compared with the parabolically tapered structure, which has been successfully used in many MMI devices.

By using two-dimensional (2D) beam propagation method, evolution of lightwave propagation inside the proposed tapered MMI structure is shown in Fig. 3. The (2,2) Padé approximant wide-angle beam propagation method and transparent boundary conditions (TBCs) are used in our simulation. In our calculation, the free space wavelength is 1.55 μm, the width of the tapered MMI section at $z = 0$, W_i, is 14 μm. The length of MMI section is determined by Eq. (13). The other parameters are same as those used above. It can be seen that the output images exhibit a uniform distribution. The output intensity

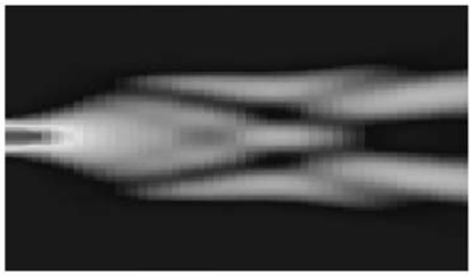

Fig. 3. Evolution of lightwave propagation inside the proposed MMI structure.

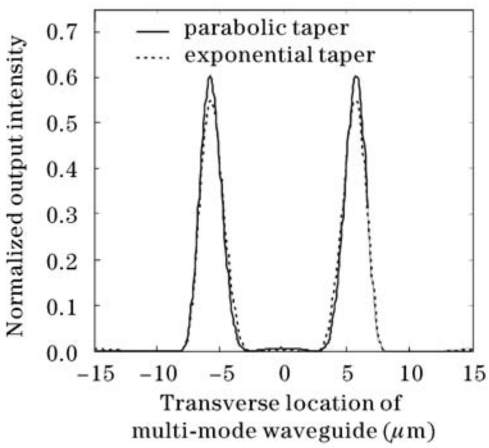

Fig. 4. Output intensity of 1 × 2 tapered MMI coupler.

distribution of the MMI couplers with the exponentially and parabolically tapered structures is also obtained, as shown in Fig. 4. The performances of these two kinds of MMI couplers are similar to each other. In our simulation, the lengths of the input and output straight waveguide are all 50 μm, the length of the linearly tapered output waveguides is 70 μm. The location of the output image obtained from the self-imaging theory usually has a deviation compared with the practical imaging location. As MMI devices are sensitive to the phase changes, the tapered structure makes this deviation more serious. So in our simulation, we adjust the location of output waveguides.

Based on the parameters we have chosen, the simulation results show that although the length of MMI section with exponential taper is reduced, the propagation loss is increased. But the performance of this kind of devices can be improved by choosing suitable structure parameters. In Fig. 5, the normalized transmitted power in MMI coupler with an exponential taper at $g = 4$ is shown, the transmission loss has a decrease compared with that at $g = 5$.

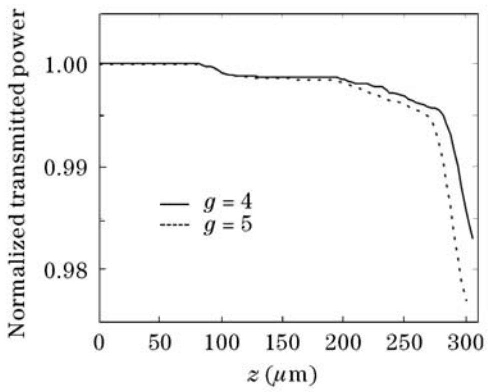

Fig. 5. Normalized transmitted power in 1×2 exponentially tapered MMI coupler for $g = 4$ and $g = 5$.

In summary, we have proposed and simulated a compact 1×2 exponentially tapered 3-dB MMI coupler. The length of this kind of couplers is shorter than that with traditional MMI structure. The results of the simulation given by the wide-angle beam propagation method show that the performance of the MMI couplers with the exponentially tapered structure is similar to the devices with the parabolically tapered structure. As a result, the exponentially tapered structure can be used in MMI devices to reduce the length of this kind of devices.

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