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Analysis of Multimode Interference Couplers with Lateral Graded-Index Profiles

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Abstract

A design scheme for multimode interference (MMI) devices with lateral graded-index (GRIN) profiles is proposed. The GRIN MMI devices having exact quadratic propagation constants can resolve the phase-error problems of step-index MMI devices.

1. Introduction

MMI devices have the advantages of compact size, good tolerance to polarization and wavelength, and design simplicity. However, the conventional implements of MMI devices are based on step-index waveguides which suffer from undesirable modal phase errors. In this letter, we propose a design scheme for MMI devices based on graded-index (GRIN) waveguides, which have benefit of no modal phase errors because of exact quadratic relationship of propagation constants. To show the proposed design scheme, a 1×2 GRIN MMI coupler is simulated as an example, and the results are compared to those of a conventional step-index 1×2 coupler.

2. Theory

For a conventional MMI structure, the lateral index profile is a step function with n_g and n_c in the guiding and cladding regions as shown in Fig.1. The waveguide structure can be designed as multimode configuration to support a large number of modes. Supposing a waveguide structure having width W is used to support m modes with mode number v = 0, 1, ..., (m-1) at a free space wavelength λ_0, its approximate propagation constant β_v is given by [1]

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

where L_π is the beat length of the two lowest-order modes.

The self-imaging property of MMI devices is essentially due to the quadratic relationship of β_v. However, in step-index MMI devices, propagation constants do not satisfy (1) perfectly, which results in serious phase-error problems [1][2], especially when the MMI sections have long lengths or support large number of modes. Therefore, a waveguide that has an exact

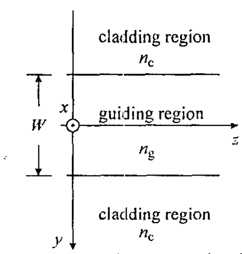

Fig.1 The top view of a conventional step-index MMI device.

quadratic relationship of propagation constants will be useful in the applications of MMI devices.

First, we analyze the interference behaviors using a general quadratic polynomial modified from (1) as

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

Note that d=2 refers to that for the conventional MMI structure, which has step-index profile. The first single-image distance is then located at $(d+1)L_\pi$ for a general excitation. By analyzing other values of d, we found that the self-imaging property is still valid for d being positive even integers. The derivation is described in the following.

For practical applications, an input field can be decomposed into the superposition of guiding modes $\psi_v(y)$. Thus, the output field after propagating a distance L can be represented as

$$f(y,L) = \sum_{v=0}^{m-1} c_v \psi_v(y) \exp(-j\beta_0 L) \exp\left[j\frac{v(v+d)\pi}{(d+1)L_\pi} L \right] \tag{3}$$

where c_v is the excitation coefficient of mode v and can be calculated by using the overlap integrals of input field $f(y,0)$ and guiding mode $\psi_v(y)$. At $L=(d+1)L_\pi/2$, the output field then becomes

$$\begin{aligned} f[y,(d+1)L_\pi/2] &= \sum_{v\,\mathrm{even}} c_v \psi_v(y) + (-1)^{d/2} j \sum_{v\,\mathrm{odd}} c_v \psi_v(y) \\ &= \left[\frac{1+(-1)^{d/2} j}{2}\right] f(y,0) + \left[\frac{1-(-1)^{d/2} j}{2}\right] f(-y,0) \end{aligned} \tag{4}$$

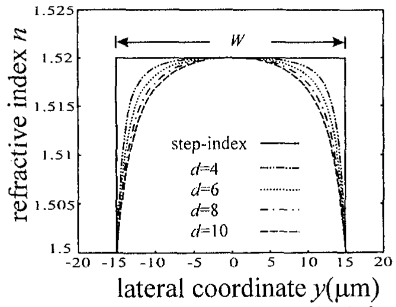

Fig.2 The lateral index profile calculated from propagation constants given by (2).

Equation (4) illustrates that the output field can be represented by a pair of images of input fields. As a result, this two-fold imaging property can be used to realize 1×2 or 2×2 3-dB couplers.

Note that a waveguide device will possess perfect two-fold imaging property at an MMI length of $(d+1)L_\pi/2$ without phase errors if its index profile is modified such that the propagation constants behave exactly as the quadratic relationship in (2). The index profiles of different values of d are reconstructed by using the inverted WKB method [3]. Except the conventional MMI structure, the occurrence of d=4 has the shortest first single image distance and will be applied to the design of a 1×2 coupler in the following analysis.

3. Numerical analysis

In the index-reconstruction procedure, the given propagation constants are interpolated from v= -0.5 to $v=v_{\mathrm{cut}}$, where v_{cut} is the cut-off mode number. By choosing $\beta_{-0.5}=k_0n_g$ and $\beta_{v\mathrm{cut}}=k_0n_s$ [3], we calculate the index profiles of various d and normalize these waveguide widths for comparison (see Fig.2).

The following waveguide parameters, n_g=1.52, n_s=1.5, λ_0=1.55μm, W=30μm, and TE polarization are chosen for simulation. Four cases (d=4, 6, 8, and 10) are studied and the corresponding index profiles are shown in Fig.2. It can be seen that the index profiles are graded and becomes more step-like for smaller values of d.

The propagation characteristics of d=4 was analyzed by using the guided-mode propagation analysis method [1]. The guiding mode of a step single-mode waveguide with a width of 1.5μm is chosen for convenience as shown in Fig.3a. Based on the analysis above, at $z=2.5L_\pi$ (L_π =940μm), the output field is a two-fold image centered at y=±6μm as shown in Fig.3b. A total loss of less than 0.20 dB is obtained without phase errors. In our analysis, the MMI section which supports 10 modes is wide enough for using as a two-port device. Obviously, the size of the device can be further reduced for compact purpose.

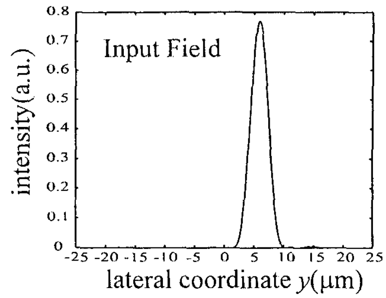

Fig.3a The field intensity distributions at z=0.

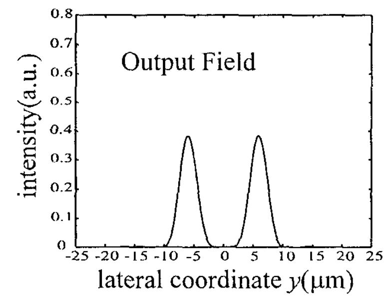

Fig.3b The field intensity distributions at $z=2.5L_\pi$ (L_π =940μm)

For comparison, the step-index MMI device with W=30μm is also analyzed. The total loss is 0.42 dB and the phase error is as large as 312 degrees for the highest order mode. Thus, it is very possible to realize MMI devices with characteristics of low loss and less phase errors by GRIN waveguides.

4. Conclusion

A design scheme for MMI devices is proposed for optical waveguide with graded-index profiles. Based on a perfectly quadratic relationship of propagation constants, numerical simulation results show that the proposed GRIN MMI devices have the two-fold imaging property without modal phase errors. Therefore, the proposed GRIN MMI 1×2 coupler can operate as a low-loss device for practical use. Details of the application will be of great interest in the future.

References

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