Waveguide beam splitters and recombiners based on multimode propagation phenomena

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Novel waveguide beam splitters and recombiners based on multimode propagation phenomena in hollow step-index waveguides are predicted and demonstrated. The splitter designs are based on symmetrically feeding the fundamental-mode field from a square cross-section waveguide, $2a \times 2a$, into a multimode rectangular guide, $2a \times 2b$ $(b > a)$. As a result of multimode superposition phenomena, unique transverse-field patterns representing different-order multiway splitting of the input field occur at predictable positions along the rectangular-guide axis. The predictions are verified experimentally at 10.6 μm with hollow dielectric waveguides but are considered to be more widely applicable.

Bryngdahl first suggested the use of light pipes to form multiple self-images of symmetric objects.[1] Ulrich *et al.* extended the concept to the replication of images of random objects in multimode waveguides[2–5] and to the possibility of fiber interferometers based on analogous phenomena.[6] The latter concept has been extended to the demonstration of low-loss directional couplers in InGaAsP rib-guide technology.[7–11] Following earlier research on the multimode propagation (MMP) characteristics of hollow circular cross-section waveguides,[12] we have predicted some novel designs for fundamental-mode field splitters and recombiners based on symmetrically fed rectangular waveguides.[13] Because these designs rely only on the excitation and propagation of waveguide modes whose field amplitudes are symmetric about the waveguide axis, for any given order of required splitting they lead to devices that are one quarter of the length of those proposed by Ulrich *et al.*[2–6] and as a result are inherently more efficient and have advantages in terms of both manufacture and use.

The theoretical and experimental research described in this Letter relates specifically to the use of hollow dielectric waveguides. However, the mode propagation in such guides is typical of that exhibited in solid-core step-index guides, with the result that the underlying concepts should be much more widely applicable. A typical MMP splitter design is shown schematically in Fig. 1. A square cross-section hollow waveguide, $2a \times 2a$, is fed symmetrically into a multimode hollow rectangular guide, $2a \times 2b$. Under the assumption that the square guide is carrying a fundamental-mode field, its propagation in the multimode rectangular guide can be modeled in terms of the excitation of a suitable set of EH_{mn} modes of the rectangular guide.[14] We can express this as

$$\mathrm{EH}_{11_{\mathrm{sq}}} = \sum A_{mn} \mathrm{EH}_{mn_{\mathrm{rec}}} \exp(i\gamma_{mn} z), \qquad (1)$$

where $z = 0$. Here the amplitude coefficients, A_{mn}, are essentially the coefficients of a Fourier series that represents the input field from the square guide. After calculating these amplitude coefficients, we can predict the field at any distance L along the rectangular-guide axis as

$$E_L = \sum A_{mn} \mathrm{EH}_{mn_{\mathrm{rec}}} \exp(i\gamma_{mn} z), \qquad (2)$$

where $z = L$. If we assume that the excited modes suffer negligible attenuation, the resulting axial variations of the transverse-field intensity profile in the rectangular guide are illustrated in Fig. 2, for the case where $b = 6a$. Figure 2 shows intensity profiles at step distances of $b^2/12\lambda$ along the axis up to a limit of $2b^2/\lambda$. In a manner that is analogous to that suggested by Ulrich *et al.*,[2–6] the sinusoidal form of the excited modes and their harmonic-phase relationships result in unique field patterns being formed at specific distances along the axis that represent perfect replications of the fundamental-mode input field. Fundamental-mode excitation may be achieved in square output guides correctly positioned at these points, thus achieving efficient energetically symmetric s-way splitting of the fundamental-mode input field. In general, assuming that $b \geq s \times a$ and the wavelength in the core of the rectangular guide is λ, the first (but not necessarily the only) point along the rectangular-guide axis at which an s-way split may be achieved is given as

$$L_{\min} = \frac{4b^2}{s\lambda} = \frac{(2b)^2}{s\lambda}. \qquad (3)$$

At this axial point, the s lateral positions across the rectangular guide (from $-b$ to $+b$) at which the square output guides should be centered are given as

$$y_s = -b + \frac{b}{s}[2(n-1) + 1], \qquad (4)$$

for $n = 1, 2, 3, \ldots s$. The axial position of the two-way field split in Fig. 2 is a point of symmetry. At

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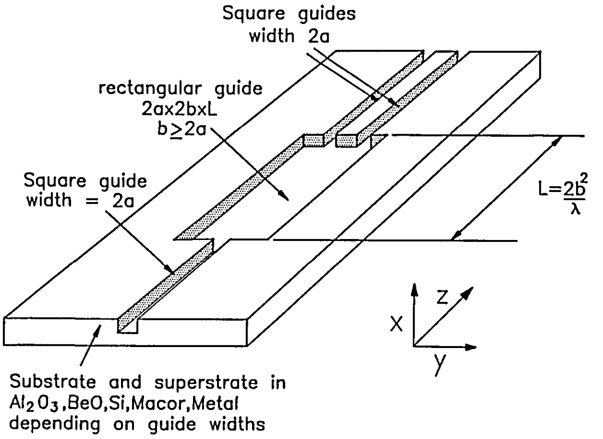

Fig. 1. Schematic diagram of a one- to two-way MMP splitter in hollow waveguide technology.

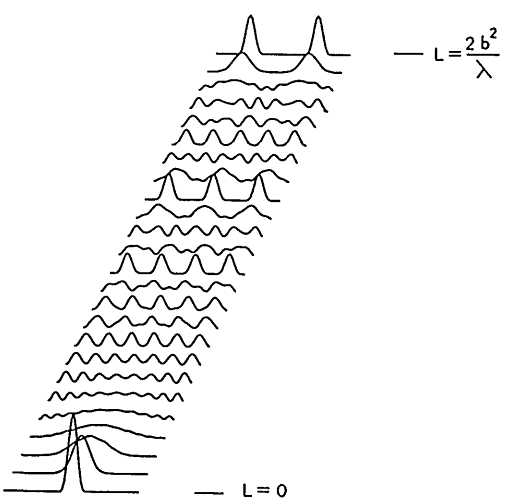

Fig. 2. Predicted transverse-field intensity profiles in a lossless hollow rectangular guide, $2a \times 2b$, where $b = 6a$, as a function of distance from the rectangular-guide entrance after the symmetric injection of a fundamental-mode field from a square guide, $2a \times 2a$.

axial points beyond this, a mirror image of the preceding field intensity pattern is reproduced with the result that the fundamental-mode field from the input guide would be reformed at the limit of a rectangular guide twice the length of that illustrated, i.e., at $L = 4b^2/\lambda$. On this basis it is clear that MMP devices also could be designed to allow the recombination of the fundamental-mode input fields carried into a rectangular guide by two or more correctly positioned waveguides or fibers. Research in progress suggests that such recombiners could be used as the basis of heterodyne mixers. Suitable combinations of splitters and recombiners also could lead to novel interferometers and modulators.

The theoretical predictions were tested experimentally with hollow dielectric waveguides in conjunction with a CO_2 laser source operating at 10.6 μm. The first experiment involved a hollow rectangular guide 0.75 mm high, 1.5 mm wide, and 212 mm long, the latter dimension providing the $4b^2/\lambda$ propagation distance required for input-field regeneration with 10.6-μm radiation. The guide was made up of four pieces of polycrystalline alumina, two T sections and two sidewalls. Polycrystalline alumina was chosen for its established properties in providing low-loss waveguides for 10.6-μm radiation.[15] The individual pieces were held together in a mount that also allowed for accurate optical alignment with respect to the input field.

After spatial filtering, the TEM_{00} output from the CO_2 laser source was focused to a waist of $0.71a$ at the entrance to the rectangular guide. The resultant field provided a good approximation to a fundamental-mode input from a $2a \times 2a$ square-sectioned waveguide.[14] The linearly polarized output from the laser and the broad dimension of the guide both lay in the horizontal plane. After accurate alignment of the waveguide with respect to the input field, the output profile was recorded by utilizing a computer-controlled scanned detector system in conjunction with a suitable lens. A typical output profile is shown in Fig. 3. This clearly indicates that the input field had been reformed. Under these conditions, the overall guide transmission was measured as 82.5 ± 0.25%.

In a second experiment, the alumina pieces of the original guide were cut to half their original length

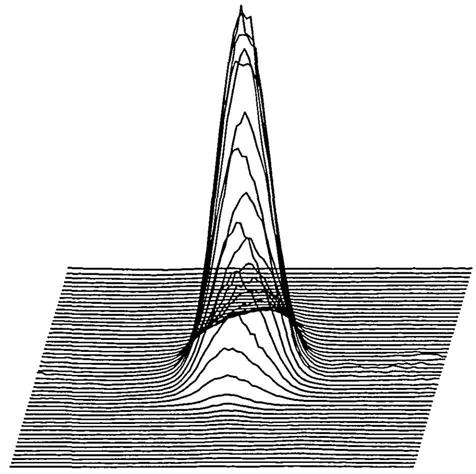

Fig. 3. Measured output-beam profile from a hollow rectangular waveguide of length $4b^2/\lambda$ illustrating regeneration of the input field.

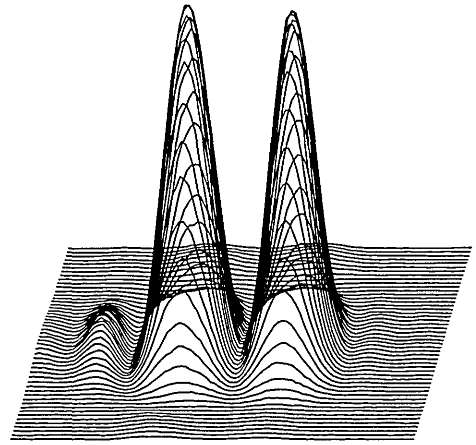

Fig. 4. Measured output-beam profile from a hollow rectangular waveguide of length $2b^2/\lambda$ illustrating two-way splitting of the input field.

and then reassembled, thus creating a hollow rectangular waveguide 0.75 mm high, 1.5 mm wide, and 106 mm long. The latter dimension then equated to the $2b^2/\lambda$ distance required for a two-way split of the input field. Once more, after accurate alignment of the guide with respect to the input beam, intensity profile measurements of the output field were made. A typical result is shown in Fig. 4. Although there is a small additional sidelobe to the left of the two main peaks, this profile clearly illustrates that a symmetric two-way splitting of the input field had occurred. Under these conditions, power measurements indicated an overall transmission of $87.5 \pm 0.25\%$.

It should be noted that, because the width of the rectangular guide used for the experiment was only twice its height, i.e., $b = 2a$, the two-way split was just resolvable. In comparison, in the theoretical plot illustrated in Fig. 2, where $b = 6a$, the components of the two-way split are well separated. However, to achieve comparable physical separation in practice would have required a rectangular guide three times the width and nine times the length of the one that we used.

With a two-way split field formed with a guide of length $2b^2/\lambda$ and a regenerated fundamental-mode field formed with a guide of length $4b^2/\lambda$, we can claim indirectly a demonstration of the recombination properties of a waveguide of length $2b^2/\lambda$ when two fundamental-mode fields are injected into it. This is in good agreement with Fig. 2 on a counterpropagation basis.

In conclusion, new forms of waveguide splitters and recombiners based on MMP phenomena have been predicted and demonstrated. These new designs, along with the realization of some earlier MMP device concepts[2–4] in newer technologies,[5,6] can provide us with a new generation of waveguide components. Applications in the fields of integrated optics, signal processing, optical computing, laser radar, and fiber-based telecommunications already have been identified. The utilization of the underlying concepts in millimetric and microwave waveguide technologies also deserves consideration. Current research is aimed at proving the principle of higher-order splitting in suitable waveguide technologies and testing more directly the characteristics of MMP interferometers and modulators.

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