Multimode interference structures – new way of passive elements technology for photonics

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The aim of this work is presentation of principles of work and properties of multimode interference (MMI) structures and their basic applications in optoelectronic circuits. We discuss the principles of simple, mirrored and multiple images formation paying attention to imaging quality, tolerance, losses, and power division in output signals. On the base of it, MMI applications in integrated optic systems – in splitters and couplers N×M technology, modulators and switches in Mach-Zehnder configuration and multiplexers are considered. The possibility of MMI production in gradient-index waveguides made by ion exchange in glass is also presented.

Keywords: multimode interference, self-imaging, optical splitters, Mach-Zehnder interferometer.

1. Introduction

Multimode interference structures have been a subject to intensive research studies for a few years [1]. It is a new technology which employs the effects of interference of mode fields in multimode waveguide and forms a multimode interference section. A typical MMI structure consists of a group of input single mode waveguides which define input field of a wide multimode section where we can observe the effects of interference of mode fields and single mode output waveguides. The image of the interference of the mode fields observed in the section MMI depends on mode properties of multimode waveguide. The propagation constants dependence on the mode number is especially important. For step-index waveguides, it is nearly quadratics and so-called self-imaging phenomena appear. As a result of these effects, the input field is reproduced in simple, reflected, and multiple images. Using self-imaging effects the power couplers and dividers 1×N and N×M can be obtained having very good optical parameters where the branching of input field is realised over a very small area of a few hundred μm. Their unique properties such as insensitivity to wavelength and polarisation, low loss, small size and ease of fabrication make MMI structures attractive for advanced applications in Mach-Zehnder switches and modulators, ring lasers, and multiplexers.

2. Principles of operation

The scheme of MMI structure is shown in Fig. 1. It consists of a group of monomode waveguides (a) which define the input field, the wide multimode section (b) where the interference effects of modal fields are observed, and the output monomode waveguides (c).

Monomode waveguides give the stable distribution of the input field \( E(x,y,0) \). This field introduced to interference section is decomposed into the modal fields \( \varphi_{nm}(x,y) \) of all modes of multimode waveguide

\[
E(x,y,0) = \sum_{n,m} c_{nm} \varphi_{nm}(x,y).
\]  

(1)

Where \( \varphi_{nm} \) is the orthogonal wave function of \((n,m)\) mode with the propagation constant \( \beta_{nm} \) and \( c_{nm} \) excitation coefficients are defined by the equation

\[
c_{nm} = \frac{\int E(x,y,0)\varphi_{nm}(x,y)dxdy}{\sqrt{\int \varphi_{nm}^2(x,y)dxdy}}.
\]  

(2)
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Each mode of MMI section propagates with a different phase velocity and hence the field at the distance $z$ is a superposition of all modal fields with the same excitation coefficient and different phase shifts

$$E(x, y, z) = \sum_{n,m} c_{nm} \phi_{nm}(x, y) \exp(-j\beta_{nm} z). \quad (3)$$

The interference pattern observed in the section MMI depends on mode properties of multimode waveguide. The particularly important is the propagation constants $\beta_{nm}$ dependence on the mode number. For step-index waveguides it is nearly quadratic and so-called self-imaging effects are observed and the input field is reproduced in simple, reflected, and multiple images. Similar quadratic dependence of the propagation constants shows also the gradient index waveguides obtained by $K^+ \leftrightarrow Na^+$ [2] and $Ag^+ \leftrightarrow Na^+$ [3] ion exchange.

There are two ways of intermode interference realisation. It is one-dimensional interference for the interference section that is multimode for the direction consistent with the section width (X) and single mode for perpendicular direction (Y) and two-dimensional interference using interference sections which are multimode in both directions. Exciting only the selected waveguide modes, the restricted interference occurs. In this lecture we restrict to one-dimensional case only.

3. Self-imaging in multimode interference structures

Self-imaging effects result from modal properties of the analysed waveguides – propagation constant dependence on the mode number, spatial distribution of modal fields and their amount [1]. In Fig. 2 is shown, for example, the propagation constants $\beta_0$ dependence on the mode number for the MMI section produced by $Ag^+ \leftrightarrow Na^+$ (silver-sodium) ion-exchange in the diffusion process through the opening of the width 16 $\mu$m, determined by the effective index method [2]. The characteristics obtained can be modeled by a quadratic equation ($A, B = \text{const}$, we omit the index 0).

$$\beta_1 = A - Bl(l + 2)$$

For the step-index waveguides with the refractive index $n$, $\beta_1$ is described by a well-known relation

$$\beta_1 = \frac{2\pi n}{\lambda} - \frac{(l + 1)^2 \pi \lambda}{4nW_e^2}$$

where $W_e$ is the effective waveguide width associated with Goos-Hanchen shifts at the boundaries. Defining the beat length $L_z$ of the two lowest order modes

$$L_z = \frac{\pi}{\beta_0 - \beta_1} \quad (4)$$

we obtain in both cases that the difference between the propagation constants of fundamental mode and mode 1 is

$$\beta_0 - \beta_1 = \frac{l(l + 2)\pi}{3L_z}$$

Substituting this dependence to Eq. (1), describing the field at $z$ in which the phase of fundamental mode is taken out of the sum as a common factor, we obtain

$$E(x, y, z) = \exp(-j\beta_0 z) \sum_i c_i \phi_i(x, y) \exp[j(\beta_0 - \beta_1)z]$$

$$E(x, y, z) = \exp(-j\beta_0 z) \sum_i c_i \phi_i(x, y) \exp[j\frac{l(l + 2)\pi}{3L_z} z]$$

So, as we see, field distribution depends on the values of exponential function. Using simple identity for mode numbers and functions

$$l(l + 2) = \text{even} \rightarrow l = \text{even}$$

$$l(l + 2) = \text{odd} \rightarrow l = \text{odd}$$

$$\phi_l(-x, y) = \phi_l(x, y) \rightarrow l = \text{even}$$

$$\phi_l(-x, y) = -\phi_l(x, y) \rightarrow l = \text{odd}$$

it can be easily shown that in the case when the propagation length satisfies condition $z = n(3L_z)$:

$$\exp\left[j\frac{l(l + 2)\pi}{3L_z} z\right] = [1 \text{ for } n \text{ even and } (-1)^l \text{ for } n \text{ odd}$$

the field distribution, accurate to constant phase factor, describes equation

$$E[x, y, n(3L_z)] = E(x, y, 0) \leftrightarrow n = \text{even}$$

$$E[x, y, n(3L_z)] = E(-x, y, 0) \leftrightarrow n = \text{odd}$$

Fig. 2. Propagation constants dependence on the mode number.
First distribution is a direct replica of the input field and the second is an image mirrored with respect to the waveguide axis of symmetry. It can be easily shown, that for the propagation length twice shorter

\[ z = \frac{n}{2} (3L_z) \]

twofold images appear, symmetrically situated to the waveguide axis of the symmetry:

\[
E\left[ x, y; \frac{n}{2} (3L_z) \right] = \sum_{l} c_l \varphi_l \exp\left( \frac{j(l + 2)n \pi}{2} \right) = \\
= \sum_{\text{even}} c_l \varphi_l (x, y) + \sum_{\text{odd}} (-j)^n c_l \varphi_l (x, y) = \frac{1 + (-j)^n}{2} \times \\
\times E(x, y, 0) + \frac{1 - (-j)^n}{2} E(-x, y, 0).
\]

It should be noticed that both distributions are shifted in phase. In general case, multi-fold images are formed at intermediate position and it can be shown [1] that at the distances N-times shorter

\[ z = \frac{n}{N} (3L_z) \]

the field will be in form of N-fold input field images

\[ E(x, y, z) = \frac{1}{C} \sum_{q} E(x - x_q, y, z) \exp(j\phi_q) \]

situated at

\[ x_q = (2q - N) \frac{W}{N}, \quad q = 1, ..., N - 1 \]

where \( W \) is the MMI width and

\[ \phi_q = n(N - q) \frac{q\pi}{N} \]

denotes the phase shifts which are inherent to the imaging properties of multimode waveguides. Depicted dependence describe so-called general interference. It can be shown that for the inputs positions

\[ x_{in} = \frac{i}{N} \quad \text{with the integer} \ i \]

some of the output images overlap, giving in general a non-uniform power distribution at the output. Only for selected input positions

\[ x_{in} = \frac{W}{2}, \quad x_{in} = \frac{W}{3}, \quad x_{in} = \frac{2W}{3} \]

the self-images with equal intensities can be observed. It is the case of so-called restricted interference when waveguide modes are selectively excited. Figure 3 presents the calculated modal field distributions of waveguide obtained through the diffusion of K+ ions through the window of the width of 36 \( \mu \text{m} \) in a time of 1 hour. Calculations are performed for equivalent one-dimensional waveguide determined by the effective index method. The diffusion window position and the place of the input field introduction for symmetrical exciting and in 1/3 of the window width are marked in the figure. It can be noticed that in the first case only symmetrical modes are excited and for any symmetrical mode number \( l \) the condition \( l(l + 2) = 4N \) (\( N = 1, 2, ... \)) is satisfied. It allows observing the self-imaging events for four times shorter propagation length (according to the propagation length from Eq. (5), simple and reflected images appear now at \( z = n(3/4L_z) \)). It is so-called symmetric interference. In the second case, the input field doesn’t excite the modes of the number 2, 5, 8, ... and the others are grouped in pairs. It can be shown that for such excitation

![Fig. 3. Wave functions of TE modes for the waveguide obtained by the diffusion of K+ ions. Waveguide is excited symmetrically and at 1/3 of the window width.](image-url)
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mode numbers fulfill the condition \( n(n + 2) = 3N \). It shortens the propagation length required for self-imaging three times (simple and reflected images appear for \( z = nL \)). Described interference is called paired interference [1]. Basic output configurations and relative phase shifts calculated from presented expressions are shown for symmetric excitation at Fig. 4 and for the excitation at 2/3 of the waveguide width in Fig. 5.

4. Numerical simulations of the wave propagation in MMI

The presented guided-mode propagation analysis requires detailed calculation of all modal fields and propagation constants. They can be easily determined only for two-di-

Fig. 4. Basic output configurations and relative phase shifts for the symmetrical excitation.

Fig. 5. Basic output configurations and relative phase shifts for the excitation at 1/3 of the waveguide width.

Fig. 6. The contour map of the field amplitude for arbitrarily excitation (a) and at the 1/3 of the window width (b).
densional multimode structures. The problems can also appear in characterisation of MMI structures with a very wide interference section and a big number of modal fields. More efficient way of the description of MMI structure, particularly in a three-dimensional case, is a FD BPM [2]. Figure 6(a) shows the contour map of the field amplitude along propagation length for the minimum reference level 0.15 of maximum value. MMI section is produced by Ag⁺ ↔ Na⁺ ion-exchange (Δn = 0.1) in the diffusion process through the opening of the width W = 16 μm excited by the field from single mode waveguide. The single mode waveguide, fabricated for the window opening w = 1.2 μm is situated at 6 μm from the structure centre. For such arbitrarily selected field introduction should excite all modes of MMI section. The input field image mirrored with respect to the MMI symmetry axis is observed at the distance 3L z = 2670 μm (3890 μm). For the distance a twice shorter the wave field divides on nearly equal parts.

Similar effects, but for the propagation length three times shorter, can be observed for more selective excitation of MMI at 1/3 of the window width — Fig. 6(b). The characteristic lengths of propagation, where the mirror and two-fold images appear are marked in the interference pattern. The input field image reflected in respect to MMI symmetry axis appear at the propagation length z = 880 μm, equal approximately to 1/3 of the propagation length for arbitrary asymmetric excitation. It corresponds to restricted paired interference.

The interference pattern in MMI shown in Fig. 7 corresponds to symmetric excitation. In such a situation only even modes MMI should get excited. The image of input field is formed at the distance L = 660 μm equal approximately to 3/4 of the coupling length for restricted paired interference.

5. Examples of MMI applications

Now, we present some examples of MMI structures applications in couplers/splitters technology of different configurations, Mach-Zehnder interferometers, passive phase shifter, and wavelength division multiplexers.

Making use of the self-imaging effects of input field power dividers and couplers 1×N and N×M can be produced, having very good optical parameters, where the branching of input field is realised on a very small area of a few hundred μm. Typically, these devices have been made using step-index technologies in different material systems, including lithium niobate, gallium arsenide, aluminium silicate on silicon, indium phosphide, and silica on silicon. A schematic diagram of one of the first 1-to-4 way beam splitters [5] with dimensions of access waveguides w = 2.6 μm and MMI geometry — W = 40 μm, L = 1324 μm is shown in Fig. 8. The planar waveguide was made using metal organic chemical vapour deposition, to grow epitaxial layers on an n-type GaAs substrate. The guides were formed by reactive ion etching to give highly reflecting vertical sidewalls.

Fig. 7. The contour map of the amplitude distribution for symmetrical excitation.

Fig. 8. Schematic diagram of a GaAs/AlGaAs 1-to-4 way beam splitter (after Ref. 5). The parameter s given for each AlGaAs layer is the aluminium concentration.

Similar, symmetric 1×N MMI couplers have been realised in silica on Si material [6]. Fibre-to-fibre losses are 0.7, 0.9 and 1.3 dB with a maximal unbalance of 0.1, 0.2 and 0.5 dB for 1×2, 1×4 and 1×8 MMI couplers, respectively. Excess losses increase with the number of outputs. The optical bandwidths are 480 nm, 240 nm, and 120 nm
for 12, 14, and 18 MMI couplers, respectively (defined for additional loss of 1 dB in the MMI couplers), so the bandwidth is inversely proportional to the number of outputs.

Novel power splitters using angled MMI couplers that allow free selection of the power splitting ratios has been proposed in Ref. 7. The device using angled MMI coupler is realized in silica on silicon technology. The diagram of the coupler arrangement is shown in Fig. 9. It consists of the 3 dB coupler with two input ports, 3 dB coupler with two output ports situated at 1/3 and 2/3 MMI section width and of a central circular MMI segment of angle $\alpha$ which join together both 3 dB couplers. The ability to select different angle allows achieving full range splitting ratio.

However, the MMI couplers rotation can cause certain difficulties in designing optical circuits, because their access waveguides are tilted at a certain angle. The another configuration of silica based 2x2 multimode interference coupler with arbitrary power splitting ratio reported in Ref. 8 is shown in Fig. 10(a). The coupler has a cladding-filled gap in a centre of its MMI region. Light injected into one of the input waveguide is divided into two light waves in region A. The two light waves then pass through region B to region C one via the core and second via the cladding. Since the core has a higher refractive index than the cladding, each light wave experiences a different phase shift. When the refractive index difference $\Delta n \sim 0.005$ and wavelength $\lambda = 1.55 \, \mu m$ the splitting ratio can change in the limit 0–1 for the gap length < 100 $\mu m$. In practice, however, the increase of the gap length increases the excess loss of the MMI couplers caused by diffraction in the gap area. This loss can be reduced by dividing the gap into several sections, Fig. 10(b).

The possibility of producing MMI structures is gradient index waveguides has been shown in Refs. 2 and 3. Figure 11 presents numerical simulations, using BPM method, of exemplary applications of MMI made with the exchange technique $\text{Ag}^+ \leftrightarrow \text{Na}^+$ for realization of symmetrical splitters 1x2 and 1x4. At the output we obtain a uniformly divided signals with the excess losses 0.714 dB and 0.85 dB, respectively. MMI structures have the window opening of

![Fig. 9. The scheme of angled MMI splitter with arbitrary power splitting ratio (after Ref. 7).](image)

![Fig. 10. The silica based 2x2 multimode interference coupler with arbitrary power splitting ratio (after Ref. 8).](image)

![Fig. 11. Numerical BPM simulations MMI structures made with the $\text{Ag}^+ \leftrightarrow \text{Na}^+$ ion exchange for the symmetrical 1x2 (a) and 1x4 (b) splitter.](image)
the width \( W = 16 \, \mu m \) and their lengths are equal to 340 \( \mu m \) and 170 \( \mu m \), respectively. Recently, a 1x4 wave splitter using Ag\(^+\) \( \leftrightarrow \) Na\(^+\) ion exchange technology for the wavelength of 1.53 \( \mu m \) has been demonstrated [9].

MMI optical waveguide couplers and splitters can be used in Mach-Zehnder interferometers (MZI) technology of different configurations. A diagram of the simplest Mach-Zehnder interferometer structure is presented in Fig. 12(a). It consists of a pair of symmetrical MMI structures working as a 1x2 waveguide splitter and coupler respectively, connected through the interferometer arms of the length \( L_A \) and separation distance \( W_A \). Figure 12(b) shows the field evolution in symmetrical Mach-Zehnder interferometer for MMI section and input waveguide widths of 8 \( \mu m \) and 1.2 \( \mu m \), respectively. Length of interferometer arms is assumed to be 1000 \( \mu m \) and their separation amounts to 4 \( \mu m \). Splitting and coupling length of MMI section is equal to 181 \( \mu m \). Excess loss is about 1 dB.

A lot of examples of modulators and switches made in Mach-Zehnder configurations are known. Figure 13(a) shows, for instance, the Mach-Zehnder interferometric switch with two MMI couplers/splitters made in silica based technology using so-called nano-mechanical effect [10]. Using is achieved by the effective -index-shifting element \( E \) in form of a cantilever situated over one leg of the interferometer. The element \( E \) was actuated by piezoelectric forces. Geometry of the device is designed in such a way that an air gap of the width \( d < \lambda \) and the evanescent field of a guided mode penetrates through the air gap into the element \( E \). Therefore the effective refractive index \( N_{eff} \) of the guided mode is modulated by air gap width variations. The results for periodic switching with a repetition rate of \( f = 1.0 \, kHz \) are shown in Fig. 13(b).

MMI structures find also applications in passive shifters technology. A new type of passive MMI phase shifters, based on modifying the waveguide width instead of modifying the length of waveguides, are proposed [11]. In comparison with the bent lines these shifters are six times less sensitive to changes in wavelength.

A novel concept to design simple guided-wave 1.3/1.55 \( \mu m \) wavelength division multiplexers has been proposed in Ref. 12. The device was made in silica based technology described in Fig. 14(a). The MMI multiplexer is schematically shown in Fig. 14(b). The input and output waveguides of the width of 2 \( \mu m \) are situated at 1/3 or 2/3 of the MMI section width (paired interference). A direct or mirrored images of the input field are formed at the device length of \( pL_x \), where \( p = 1, 2, \ldots \) and \( L_x \) is the beat length of the lowest order modes. An MMI structure can separate...
two wavelength $\lambda_1$ and $\lambda_2$ if it is in a bar state for one wavelength and a cross state for the other, i.e.,

$$L_d = p_1 L_{z,\lambda,1} = (p_1 + p_2) L_{z,\lambda,2}$$

where $L_{z,\lambda,1}$ is the beat length at wavelength $\lambda$, $p_1$ is a positive integer and $p_2$ is an odd integer. For values $p_1 = 5$ and $p_2 = 1$ the MMI structure is in a cross state at 1.3 $\mu$m and in a bar state at 1.55 $\mu$m at the length $L_d = 5L_{z,\lambda,1} = 6L_{z,\lambda,2}$. The device functions either as a multiplexer or demultiplexer, depending on the direction of light propagation. A demultiplexer with an insertion loss of 0.5 dB and contrasts of 40 dB at wavelength 1.3 $\mu$m and 34.5 $\mu$m at 1.55 $\mu$m was demonstrated.

One of the main advantages of MMI devices is their large bandwidth. The MMI couplers are also effectively insensitive to wavelength over the desired wavelength range. These properties find application in phase-array wavelength division multiplexers. Design of phase-array division multiplexers using multimode interference couplers has been presented in Ref. 13. These devices, which operate on N equally spaced wavelength channels, consist of two MMI couplers connected by an array of N monomode waveguides. The MMI couplers work as power splitters/combiners, and the waveguide array is the dispersive element. These multiplexers can function as NxN wavelength-selective interconnecting components. Bragg gratin-assisted MMI-coupler for add-drop multiplexing has been also presented [14,15].

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References