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Analysis of the characteristics of a waveguide device for combining external optical beams

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Received August 28, 2022
Revised November 6, 2022
Accepted December 4, 2022

The design of a planar waveguide combiner of light beams, which performs the summation of a set of external light beams, is proposed. Combiner design options are considered and a 3D version with optical decoupling is proposed. The calculations of the operating parameters of the elements of the combiner depending on the values of the refractive indices of the layers of the structure are done. The minimum dimensions of the input/output diffractive elements of the combiner are estimated.

Keywords: optical integrated circuits, optical beam combiner, diffraction grating, waveguide.

DOI: 10.21883/EOS.2023.01.55523.4035-22

Introduction

In optical integrated circuits (OIC) designed for parallel processing of information, a device is required for summing beams in free space [1,2]. There are two types of devices associated with combining optical signals. The first type of devices can include an optical multiplexer used for compacting optical signals and increasing the bandwidth of channels. Optical signals in a multiplexer differ in wavelength, polarization, or the propagation angle of the waveguide mode [3–8]. The signals propagate independently over a single channel, and are separated at the output using a demultiplexer. The second type of device, called an optical unifier, is used to sum several optical beams in order to amplify them. Combinators are used to produce high-power laser beams [9–11], amplify weak optical signals in astronomy and microscopy [12,13], as well as to perform vector-matrix optical transformations in associative memory devices and switching circuits [14,15].

The proposed waveguide combiner, designed for summing optical beams, can be implemented in the form of a matrix [16]. In addition, a planar beam unifier can be used as an optical multiplexer for spectral channel densification in the case of manufacturing input lattices with different periods. In this paper, a theoretical analysis of the characteristics of the device under development, made in the form of a thin-film multilayer 3*D* structure, is carried out.

1. Construction of a multilayer waveguide unifier

The technology of manufacturing a waveguide unifier is similar to the technology of manufacturing a waveguide divider of light beams [17]. The unifier, like the divider, consists of a common optical bus in the form of a thin-film planar waveguide and a line of input and output elements based on relief diffraction lattices. Since divisors and combinators are supposed to be used together for vector-matrix transformations [16], the unified technology of their manufacture makes it possible to simplify the process of creating an OIC.

Due to the reversibility of optical processes, it would be possible to use the divider as a unifier, making the output elements of the divider the input elements of the unifier. But this will be ineffective, since the light introduced into the first input elements will be partially or even completely displayed on the subsequent input elements. To overcome this disadvantage, we propose to apply an optical isolation — a buffer dielectric layer separating the input lattice from the main waveguide (Fig. 1).

The buffer layer does not allow the waveguide mode of the main waveguide to be output through the input lattices. Input waveguides are formed on the surface of the buffer layer to communicate with the main waveguide. In order for the angle of propagation of the waveguide mode in the

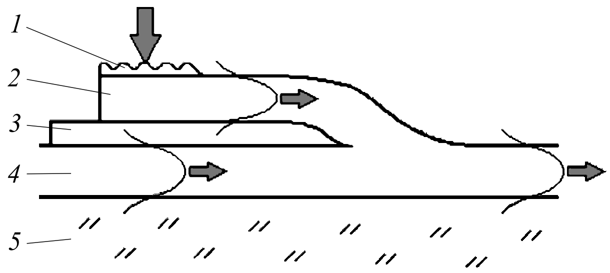

Figure 1. Element of the 3*D* light beam unifier. *1* — lattice input element (As_2S_3), *2* — input waveguide ($As_{20}S_{80}$), *3* — buffer layer (MgF_2), *4* — main waveguide ($As_{20}S_{80}$), *5* — substrate (glass K8).

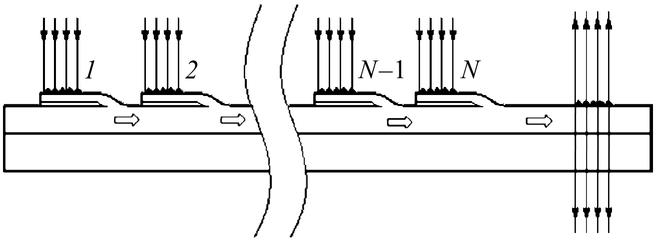

Figure 2. The unifier N of light beams based on a planar waveguide with optical isolation.

input waveguide to coincide with the angle of propagation of the mode in the main waveguide, it is necessary to select the thickness of these waveguides based on the condition of phase matching [18].

For effective decoupling of the input lattice and the optical bus, it is necessary that the thickness of the buffer layer be greater than the depth of penetration of the waveguide mode into this medium [18]. For example, for a waveguide made of chalcogenide glass As_2S_3 ($n = 2.5$), and a buffer layer made of magnesium fluoride MgF_2 ($n = 1.34$), the penetration depth is about $0.05\,\mu$m. Thus, a buffer layer with a thickness of more than $0.1\,\mu$m will provide the required decoupling.

In order to avoid reflection losses in the area of docking of the input waveguides with the main one, they must be made of the same material.

The thicknesses of the main and input waveguides should be chosen so as to satisfy the condition of mode matching in these waveguides. This means that the propagation angle of the waveguide mode of one waveguide must be equal to the propagation angle of the mode of the other waveguide. This condition is automatically fulfilled if both waveguides are of the same thickness.

The intensity losses of the optical mode at the vertical transitions of the integrator layers can be minimized to units of percent by means of smooth blurring of the boundaries and small thicknesses of the waveguide and buffer layers.

In the case of a multimode main waveguide, it is possible to reduce the length of the scattering region of the waveguide junction by reducing the thickness of the input waveguide. To do this, the thicknesses of the waveguides are selected so that the zero mode propagates in the input waveguide, and mainly the — mode of a higher order. In this case, the thickness of the input waveguide will be less than the thickness of the main waveguide.

In our case, the diffraction lattices of the input are recorded by radiation with a wavelength of 532 nm in the layer of the actinic photoresist As_2S_3, and the main and input waveguides are made of the material $As_{20}S_{80}$, insensitive to this wavelength.

The general scheme of the light beam unifier is shown in Fig. 2. N input beams from free space are introduced into the main waveguide using N diffraction input elements with optical isolation. The beam with the total intensity is output into free space as a result of diffraction on the output lattice of the main waveguide.

2. Advantages of chalcogenide glasses in comparison with oxide glasses for the manufacture of waveguides

The values of the refractive indices of the waveguides and the surrounding media determine the characteristics of the input/output elements of the light beam unifier. Consider two types of waveguides with different refractive indices at the working wavelength $0.63\,\mu$m:

- the diffusion waveguide in oxide glass K8, $n = 1.52$;
- the thin-film waveguide made of chalcogenide glass $As_{20}S_{80}$, $n = 2.2$. The substrates are made of oxide glass K8, $n = 1.5163$.

2.1. Waveguide thickness

With an increase in the refractive index of the waveguide, its thickness decreases, sufficient to maintain a certain number of modes. For a single-mode waveguide made of oxide glass, its thickness is about $1.5\,\mu$m, and for a 4-mode waveguide — about $12\,\mu$m. For chalcogenide glass waveguides, these thicknesses are $0.04\,\mu$m and $0.7\,\mu$m, respectively. Thus, the use of materials with a higher refractive index makes it possible to reduce the thickness of the waveguides by an order of magnitude.

2.2. Light input efficiency

The efficiency of the input of radiation into the waveguide means the ratio of the intensity of the waveguide mode to the intensity of the input beam. The wave diffracted by the lattice in a planar waveguide is deformed along one coordinate, forming a waveguide mode. It turned out that the maximum efficiency of radiation input into the waveguide is possible with certain parameters of the input beam [19]. Let us consider a beam with a Gaussian intensity distribution:

$$I = I_0 \exp[-(x - c_0)^2/s_0^2],$$

where $2s_0$ is the effective beam width, and c_0 is the displacement of its center relative to the left end of the corrugated waveguide section, I_0 is the intensity of the beam in the center. For such a beam, the maximum input efficiency of radiation is about 80% and occurs under the conditions

$$\alpha s_0 = 0.68,$$

$$\alpha c_0 = 0.5,$$

where α — the leakage coefficient of the waveguide mode.

For example, consider lattices with diffraction efficiencies of 10 and 30%. The leakage coefficient is estimated by the formula [20]

$$\alpha = \ln(1 - \eta_{\text{dif}})/L_{\text{ef}},$$

where h_{dif} is the diffraction efficiency of the lattice, and L_{ef} is the effective waveguide length (zigzag wave period) equal to

$$L_{\text{ef}} = 2h_{\text{ef}}\,\text{tg}\,\theta, \tag{1}$$

where h_{ef} — the effective thickness of the waveguide [18]; θ — the propagation angle of the waveguide mode.

Let us choose c_0 optimal and find optimal values for s_0. For a 4-mode waveguide made of oxide glass, the beam width for maximum input will be 6 and 2 mm, respectively, and for a 4-mode waveguide made of chalcogenide glass — 70 μm and 25 μm, respectively. It can be seen that the use of chalcogenide waveguides with a higher refractive index makes it possible to reduce the size of the input elements by almost two orders of magnitude.

2.3. Polarizing properties of input elements

Planar waveguides have polarizing properties and can be used as polarizers [21].

To evaluate the polarization properties of the input element, consider the phenomenon of multipath interference when light is introduced into a planar waveguide [22]. The multiplicity of interference is determined by the ratio of the length of the input lattice L to the effective length of the waveguide L_{ef}, determined by the condition (1). In this case, the intensity of the injected light as a result of multipath interference is expressed as

$$I(\phi) = I_0(1 - \cos N\theta)/(1 - \cos\theta),$$

where θ determines the propagation angle of the radiation introduced into the waveguide, and $N = L/L_{\text{ef}}$ — the multiplicity of interference. Thus, as the length of the input element increases, the angular width of the waveguide mode decreases. The angular width of the waveguide mode refers to the range of angles of propagation of radiation in the waveguide, at which the intensity of the mode is no more than two times different from the intensity of radiation introduced at the angle of the waveguide mode. When the difference between the excitation angles of the TE and TM modes is greater than the angular width of the mode, the input element will become more sensitive to the polarization of the input beam.

Since the maximum input of radiation occurs at a certain lattice length, the degree of polarization of the optimized input element will be fixed. We will show this using examples of 4-mode waveguides made of chalcogenide and oxide glasses with different lengths of the input lattices defined in Section 2.2. Fig. 3 shows the dependence of the input efficiency on the angle of radiation input into the chalcogenide waveguide.

The dashed lines correspond to a lattice with a diffraction efficiency of 30, and the solid ones — 10%, while the length of the lattices corresponds to the maximum input of radiation into the waveguide. It can be seen that with a difference in the input angles of TE- and TM-modes of the order of 1°, the polarizations can be separated. The

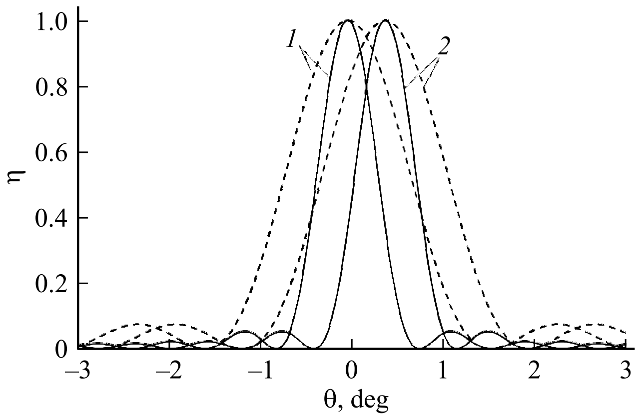

Figure 3. Dependence of the relative efficiency of radiation input η into a chalcogenide waveguide on the input angle θ for various polarizations: *1* — for TE-polarization, *2* — for TM-polarization.

polarization properties of the elements of the combiner can be used as polarization filters when optical signals are noisy with interference.

For oxide waveguides, the peak width is almost the same, but the difference between the input angles of TE and TM modes for a 4-mode waveguide is more than two orders of magnitude smaller and is 0.005°, and the graphs are indistinguishable at all.

2.4. Light output efficiency

The intensity of the light output from the waveguide is determined by the lattice length and its diffraction efficiency [20]:

$$I_{\text{out}} = I_0[1 - (1 - \eta_{\text{dif}})^{-L/L_{\text{ef}}}],$$

where I_0 — the intensity of the waveguide mode; η_{dif} — the diffraction efficiency of the lattice; L — the lattice length.

Consider the case of a sinusoidal lattice with an efficiency of 30%. For a 4-mode oxide glass waveguide, the estimated lattice length with an output efficiency of 95% is 6 mm, and for a 4-mode chalcogenide waveguide — about 70 μm. Thus, the difference in the size of the output elements, as in the case of the input elements, is almost two orders of magnitude.

A sinusoidal diffraction lattice outputs light to both media adjacent to the waveguide, and the ratio of intensities output to different media when corrugating the waveguide at the boundary with air is defined as [23]

$$\frac{P_c}{P_s} = \frac{[N_f^2 - (n_f^2 - n_s^2)\sin^2(N_f kh)]N_c}{N_f^2 N_s},$$

where $N_{c,f,s} = [n_{c,f,s}^2 - (n^* - \lambda/d)^2]^{1/2}$, $n_{c,f,s}$ — refractive indices of air, waveguide and substrate, respectively; n^* — effective refractive index of waveguide; h — thickness of waveguide; d —corrugation period.

Estimates of the values of the light intensities derived orthogonally from the oxide and chalcogenide waveguides showed that for an oxide waveguide about 60% of the light is output to the substrate, and the remaining 40% — into the air, and this ratio practically does not change when the thickness of the waveguide changes. Whereas in a chalcogenide waveguide, by selecting the thickness of the waveguide, up to 80% of the light output through the substrate can be obtained. Thus, in waveguides with a high refractive index, by changing the thickness of the waveguide and the period of the output lattice, it is possible to achieve the output of light mainly into one medium.

3. Minimum dimensions of the elements of the unifier

The integrated optical design of the optical beam unifier implies the execution of its elements with minimal dimensions. On the other hand, there are factors for limiting size reduction that should be taken into account.

Reducing the size of the input/output elements will contribute to an increase in the diffraction divergence of the beams. For the lattice output element, the divergence angle $\Delta\theta$ will be determined by the ratio

$$\Delta\theta \sim \lambda/(nL),$$

where λ — the wavelength of light, n — the refractive index of the lattice, L — the lattice length. Output lattices made of chalcogenide glass with a length of $15\,\mu$m will lead to an angular divergence of the output beams of the order of 1°. This should be taken into account when agreeing with the registration system.

The maximum efficiency of the input/output of light by the lattice applied to the waveguide is determined by the length of the lattice. As shown above, for a 4-mode chalcogenide glass waveguide As_2S_3, this length is about $70\,\mu$m, and for a single-mode — about $20\,\mu$m. Therefore, in order to ensure efficient input/output, the length of the lattices must be at least a certain value.

Thus, the dimensions of the unifier will be determined by the requirements imposed on them. Depending on the field of application of the device of which they are a part, it is possible to choose the length of individual elements that is optimal in terms of miniaturization of the circuit, divergence of working beams, their intensity and polarization.

The maximum number of input beams of the combiner will be determined by the losses on the input elements and in the waveguide. To ensure the reliability of the result of summing the N beams, the total losses during propagation of the introduced beams should not exceed the intensity of one of these beams.

Conclusion

A new design of the device — an optical beam unifier designed for summing a set of parallel beams in free space is proposed. It is implemented in the form of a multilayer structure based on planar waveguides and diffraction light input/output elements with optical isolation.

The advantages of chalcogenide glass waveguides with a high refractive index for obtaining the minimum dimensions of the device and improving the polarization selectivity of the input elements are shown. The use of such waveguides makes it possible to reduce the geometric dimensions of the input/output elements of waveguide structures in comparison with oxide glass waveguides: the thickness of the waveguide — by an order of magnitude, the length of the input/output element with maximum efficiency — by two orders of magnitude. The efficiency of light output towards the substrate from a waveguide with a higher refractive index also increases by 20% due to the redistribution of the intensity of the beams exiting into adjacent media.

Currently, all technological stages have been worked out for the practical implementation of the optical beam unifier scheme based on chalcogenide waveguides — application of chalcogenide and buffer layers in high vacuum, obtaining input and output holographic lattices of relief type. Technical specifications for possible parameters of the elements of the unifier circuit for various applications are being formed.

Funding

The work was carried out as part of the State assignment of the Ministry of Education and Science of the state reg. № 121022000126-9.

Conflict of interest

The authors declare that they have no conflict of interest.

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