described in eqn. 6. It can be seen that the average sidelobe level and the beamwidth are approximately equal to −30 dB and 3·2°, respectively. In Fig. 3, the beampattern is obtained

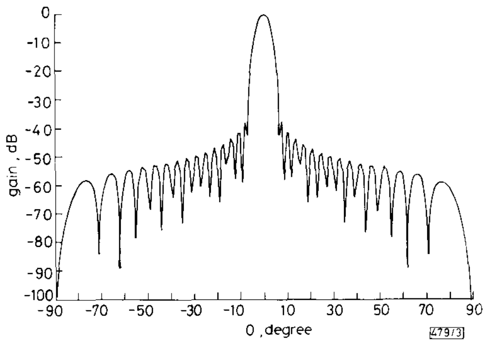

Fig. 3 *Array beampattern obtained using proposed alternative approach*

by the alternative approach described by eqn. 7. In this case, i is set to two and the regions of integration are

$$[\phi_{l_1}, \phi_{u_1}] = [6°, 90°]$$

and

$$[\phi_{l_2}, \phi_{u_2}] = [-90°, -6°]$$

It can be seen from the figure that the sidelobe level is improved approximately by 25 dB at the expense of widening the beamwidth to about 4·6°.

Conclusion: It is shown that using the proposed computer-aided approach, an array beampattern, with an adjustable beamwidth corresponding to the minimum average sidelobe level for certain specified spatial regions, can be achieved. This simple approach may be extended to a more general situation where the signals involved are broadband signals incident with a certain elevation angle. This can be accomplished by an integration over the required regions of frequency and spatial angles. Note that this is applicable to both broadband and narrowband beamforming structures.

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NONLINEAR Y-JUNCTION COUPLER

Indexing terms: Integrated optics, Nonlinear optics, Optical connectors and couplers

We propose a new structure for a symmetric single-mode Y-junction coupler to achieve an insertion loss down to 0·22 dB by using the optical Kerr effect in a nonlinear medium. The power dependence of the coupling efficiency and a picture of wave propagation are presented and discussed.

The single-mode Y-junction coupler is one of the most important elements in optical-waveguide circuits. The performance of this coupler has been investigated extensively. For a symmetric single-mode Y-junction coupler, there is an inherent 3 dB insertion loss when the light comes from one arm of the branching fork.[1] In this letter we propose a new structure for the symmetric single-mode Y-junction coupler using the nonlinear Kerr effect. With proper design and input power, the insertion loss can be greatly reduced to 0·22 dB.

The proposed Y-junction coupler is shown in Fig. 1. Two-dimensional structure is considered for simplicity. The structure can be divided into three sections, as shown in the figure.

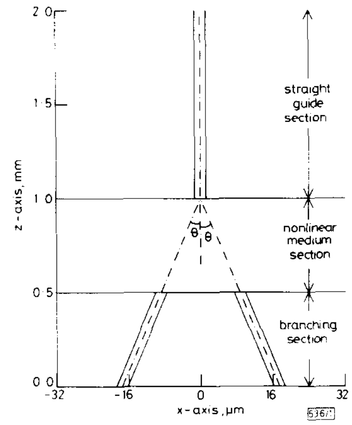

Fig. 1 *Schematic structure of the nonlinear Y-junction coupler*

In the branching section, the separation of the two branches is decreased toward the section end down to a distance that is large enough to prevent the mutual coupling between two branches. The nonlinear medium section lies between the branching section and the straight guide section. When the guided mode of one of the branches carrying high power is coupled to the nonlinear medium, the spatial soliton can be excited. Since the thickness of the nonlinear medium is only about 500 μm, the absorption and scattering loss of the spatial soliton propagating in the medium can be neglected. In the meantime, the loss due to reflections at the interfaces between the nonlinear medium and the other sections can be neglected by choosing a suitable nonlinear medium. The main loss occurs when the spatial soliton is coupled to the straight guide section, because the propagation direction of the spatial soliton does not coincide with the straight guide. This coupling loss is similar to the bending loss of an ordinary waveguide.

The electrical field of the optical wave is written as $E(x, z, t) = \mathcal{E}(x, z) \exp i(\beta k_0 z - \omega t)$, where k_0 is the wave number in free space and β is the effective index of refraction. The electric field satisfies the wave equation

$$-2i\beta k_0 \frac{\partial \mathcal{E}}{\partial z} + \frac{\partial^2 \mathcal{E}}{\partial x^2} + k_0^2[n^2(x, z) - \beta^2]\mathcal{E} = 0 \qquad (1)$$

and the boundary conditions. The propagation beam method[2] is used to calculate the wave propagation in the coupler. For the calculation, we choose the following numerical data: $n = 1{\cdot}55$ for the waveguide cladding, 1·57 for the waveguide core and $1{\cdot}55 + n_{2l}|\mathcal{E}|^2$ for the nonlinear medium,[3] $n_{2l} = 5{\cdot}3 \times 10^{-10}\,\text{m}^2/\text{W}$. The thickness of the waveguide core is 2·5 μm and the free space wavelength $\lambda_0 = 2\pi/k_0 = 1{\cdot}3\,\mu$m.

Referring to Fig. 1, an eigenmode of the waveguide is assumed to launch from the left branch. The wave propagation along the structure is shown in Fig. 2. Since the structure is symmetric, we will get the same result if an eigenmode is launched from the right branch.

Because the refractive index of the nonlinear medium is power dependent, different input waves excite different spatial solitons in the nonlinear medium. When the mismatches of the propagation constant and the field distribution between the spatial soliton in the nonlinear medium and the eigenmode of the straight waveguide increase, the insertion loss increases. We define the coupling efficiency as the ratio between the output power P_{out} and the input power P_{in}. In Fig. 3, we plot the coupling efficiency P_{out}/P_{in} as a function of normalised

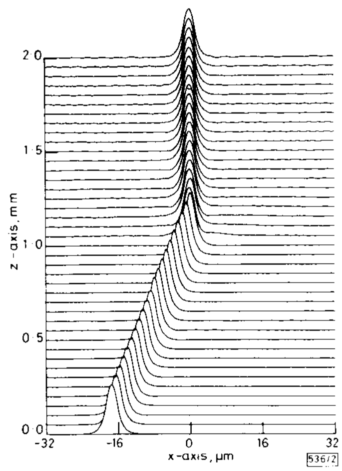

Fig. 2 *Field $|E|$ as it propagates from the left branch, through the nonlinear medium, to the straight waveguide at optimal input power P_0*

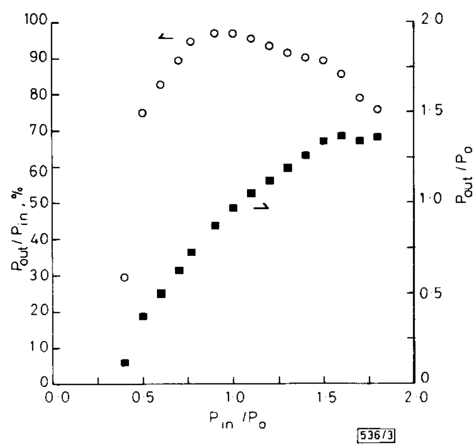

Fig. 3 *Coupling efficiency and normalised output power as a function of normalised input power P_{in}/P_0*

○○○ coupling efficiency P_{out}

■■■ normalised output power P_{out}/P_0

input power P_{in}/P_0, where $P_0 = 0{\cdot}214\,W/mm^2$. When $P_{in} = P_0$, the coupling efficiency attains its maximum value, over 95%, i.e. the minimum insertion loss of the structure is less than 0·22 dB. When the normalised input power lies between 0·7 and 1·4, the insertion loss of the structure does not exceed 10% or 0·46 dB.

The nonlinear Y-junction coupler can be generalised to an N to 1 coupler. If the branching angle between one of the branches and the straight waveguide increases, the coupling loss increases. Therefore, the waves incident from an outside branch suffer a higher loss. On the other hand, if we keep the angle small, we are forced to lengthen the nonlinear medium and the loss due to scattering and absorption in the nonlinear medium increases.

In conclusion, we have proposed a new structure for a symmetric single-mode Y-junction coupler, where a medium with Kerr nonlinearity is used. When the wave is incident from one of the branches, the insertion loss of the structure is very small compared to the 3 dB loss of the ordinary symmetric single-mode Y-junction coupler. The nonlinear coupler can be used in time division multiplexing (TDM) systems, and it is expected to have many other applications in all-optical signal processing.

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HIGH PERFORMANCE RESONANT TUNNELLING STRUCTURES ON GaAs SUBSTRATES

Indexing terms: Semiconductor devices and materials, Gallium arsenide, Tunnelling

GaAs-based resonant tunnelling structures of high quality were grown by molecular beam epitaxy. Room temperature peak-to-valley ratios of 4·8 for a GaAs/AlGaAs double barrier quantum well, 4·1 for GaAs/AlGaAs with InGaAs quantum well and 5·9 for GaAs/AlGaAs with adjacent InGaAs 'prewell' were obtained, in connection with reasonable peak current densities.

Key parameters in the performance of resonant tunnelling structures based on double barrier quantum wells (DBQW) are peak current density j_p and peak-to-valley ratio (PVR) in the I/V characteristics. The optimisation of a structure to obtain high j_p is well understood, but the influence of structural and layer growth parameters on PVR has remained rather elusive. Theoretical investigations[1] have pointed out the limitation of PVR by inelastic scattering (which crucially depends on material) and interface quality. The practical limits for the obtainable PVR are unclear. Previously PVR in GaAs/AlGaAs structures at room temperature has been below 4.[2]

The work presented in this letter was aimed at

(i) trying to improve the performance, in particular PVR, of device-oriented DBQW structures in the GaAs/AlGaAs system and

(ii) the assessment of the advantages of inserting pseudomorphic InGaAs layers either as a central potential well or as a small-bandgap 'prewell' adjacent to a conventional DBQW.

A central InGaAs quantum well allows the control of the resonance voltage independent of other structural parameters. Experimental data on such structures is scarce and seems to indicate that up to now their performance is clearly inferior to those with GaAs well (PVR < 2).[3] It has recently been demonstrated that an InGaAs prewell can enhance both the PVR and j_p.[4] This is attributed to a lowering of the space charge barrier for the injected electrons.

The design of our layer structures was guided by previous optimisations in DBQW's realised by metalorganic vapour phase epitaxy.[5]

The essential parts of the structures are shown in the lower parts of Figs. 1–3. Our standard structure (A, Fig. 1) consists of 30 Å wide $Al_xGa_{1-x}As$ barriers with $x = 0{\cdot}6$ and a 40 Å GaAs well. It is sandwiched between 150 Å thick undoped