GaAs–GaAlAs Heterostructure Single-Mode Channel-Waveguide Cutoff Modulator and Modulator Array

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Abstract—**A GaAs single-mode channel-waveguide cutoff modulator t utilizes a GaAs–GaAlAs heterostructure and a linear array of such dulators are reported for the first time. We have measured a cutoff tage as low as 9.0 V and an extinction ratio greater than 20 dB at optical wavelength of 1.3 μm in a basic modulator that utilized a As–$Ga_{0.93}Al_{0.07}As$ heterostructure with a 0.9 μm thick GaAs epitax-layer together with a ridge channel 2.5 mm in length and 5.0 μm in dth. We have also succeeded in the realization of a high packing sity (500 channels/cm) linear array of such cutoff modulators in same GaAs substrate with equally satisfactory results. An RF ndwidth of 2.5 GHz has also been measured with the elementary dulator of such array. As in the case for $LiNbO_3$ substrates, the As-based integrated optic modules that result from integration of ch cutoff modulator arrays, microlens arrays, and planar acous-ptic or electrooptic Bragg diffraction grating arrays in a common bstrate may be used to perform multiport switching, computing, and f signal processing.**

I. Introduction

ELECTROOPTICALLY-CONTROLLED guiding and cutoff modulation of a light beam in GaAs [1], [2], NbO_3 [3]–[7], $KNbO_3$ [8], and glass [9] waveguides ve been reported heretofore. Both the planar waveguide scribed in [1] and the channel waveguide in [2] were rmed using an epitaxial layer of GaAs with a doping vel that differed from the GaAs-N^+ substrate. Due to e very small difference in refractive index between the itaxial layer and the substrate, such homostructures re-ired a relatively thick epitaxial layer for guiding even r single-mode propagation. As a result, the cutoff mod-ators constructed required relatively high drive volt-es, namely, 130 and 20 V, respectively.

In the present paper, we report on the first GaAs single-ode channel-waveguide cutoff modulator that utilizes a aAs–GaAlAs heterostructure, and a high packing den-y linear array of such modulators on a common sub-rate. We have measured desirable characteristics such relatively low driving voltage and large RF bandwidth th such cutoff modulators at three optical wavelengths. rst, the device structure and the principle of operation the modulators are described. The fabrication proce-res for the basic modulator and the modulator array are en detailed. Subsequently, the experimental results are presented and discussed. Finally, a brief comparison between the proposed modulator and some of the existing modulators is made.

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II. Device Structure and Principle of Operation

The configuration and structure of the basic cutoff modulator is shown in Fig. 1. It is to be noted that the ridge channel waveguide is oriented along the direction [011] on the (100) plane. Through tailoring of both the waveguide dimension and the refractive index difference between the guiding layer and the substrate, the mode index of the channel waveguide is made very close to the substrate index. In operation, an external electric field is applied along the [100] direction, namely, the x axis. It is readily shown that as a result of this external electric field, E_x, the new principal axes y' and z' are rotated by 45° on the (011) plane, as indicated in the inset of Fig. 1. The resulting principal indexes of refraction are given as follows:

$$n_{x'} = n_0 \tag{1a}$$

$$n_{y'} = n_0 - 1/2\, n_0^3 r_{41} E_x \tag{1b}$$

$$n_{z'} = n_0 + 1/2\, n_0^3 r_{41} E_x \tag{1c}$$

in which n_0 is the refractive index of bulk GaAs and r_{41} is the relevant electrooptic coefficient (10).

Clearly, cutoff modulation is facilitated by electrically-controlled reduction of $n_{y'}$ through E_x and r_{41} for the TE-mode light propagating in the [011] (Z') direction. The electric field E_x is in turn produced by application of a reverse bias voltage to the Schottky barrier contact. Thus, controlled guiding and intensity modulation of the device are produced by the reverse bias voltage.

III. Fabrication of Basic Cutoff Modulator and Modulator Array

A single cutoff modulator as well as a linear array of identical cutoff modulators have been successfully fabricated. First, a planar GaAs–GaAlAs heterostructure with an aluminum concentration of approximately 7 percent and a GaAs epitaxial layer 0.9 μm thick as illustrated in Fig. 1 was grown on an X-cut N^+ substrate using an in-house LPE system. After successful optical guiding had been verified experimentally, a Ti/Au thin-film strip 5.0 μm in width and 2.5 mm in length was deposited on the planar waveguide along the [011] direction. The Ti–Au

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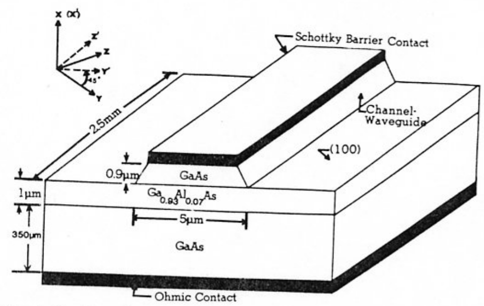

Fig. 1. Configuration and dimensions of a basic GaAs-GaAlAs heterostructure single-mode channel-waveguide cutoff modulator. Note that the channel-waveguide lies along the [011] direction or Z' axis.

film served as the mask during the wet etching process for formation of the ridge channel waveguide [11] as well as the Schottky barrier contact. The wet etching solution [12] was composed of HCl, H_2O_2, and H_2O in the ratio of 80:4:1, and provided an etching rate of 1.1 μm/min at room temperature. Both basic channel waveguides 2.5 mm long with channel widths of 4, 5, and 6 μm, and channel waveguide arrays of identical channel parameters were successfully formed using the fabrication steps just described. The parameters and waveguide orientations of both the basic modulator and the modulator array are given in Table I. Finally, after formation of an ohmic contact on the bottom face of the specimen, both end faces were cleaved to facilitate edge coupling for subsequent electrooptic experiments. Figs. 2 and 3, respectively, show the photograph of one of the cleaved end faces of the basic modulator and the modulator array. The finished sample was then mounted on a special IC chip and placed in a device holder for detailed experimentation.

IV. Experimental Results

A. Basic Modulator

Optical guiding and propagation as well as cutoff modulation in the ridge channel device were performed at three laser wavelengths, namely, 1.06, 1.15, and 1.3 μm. Excitation of single-mode (TE_0) propagation was accomplished using edge coupling. Single-mode guiding was confirmed at all three wavelengths for the 5 and 6 μm channels. No guiding was observed with the 4 μm channel, however, indicating that this channel width was too narrow. The photographs of the output light beams obtained at 1.15 and 1.3 μm wavelengths for the 5 μm channel device under various reverse bias voltages are shown in Fig. 4(a) and (b), respectively. These sets of photographs together with those obtained at 1.06 μm (not shown) clearly indicate that well-defined single-mode guiding and intensity modulation with high extinction ratio were obtained at all wavelengths. The plots for relative output light intensity as a function of the applied dc voltage are shown in Fig. 5. From these plots we see that

TABLE I
WAVEGUIDE DIMENSIONS AND ORIENTATIONS OF GaAs/GaAlAs HETEROSTRUCTURE SINGLE-MODE CUTOFF MODULATOR AND MODULATOR ARRAY

Common Parameters	
Channel width	5 μm
Channel depth	0.9 μm
Waveguide type	Ridge channel
Etching solution	$HCl:H_2O_2:H_2O$ = 80:4:1
GaAlAs thickness	1 μm
Al concentration	7 percent
Schottky barrier contact	Ti/Au, 4725/750 Å thick
Substrate orientation	(100)
Waveguide direction	[011]
Basic Cutoff Modulator	
Channel and electrode length	2.5 mm
Cutoff Modulator Array	
Separation between adjacent channels in array	20 μm
Channel and electrode length	3.0 mm
No. of channels	10
Packing density	500 channels/cm

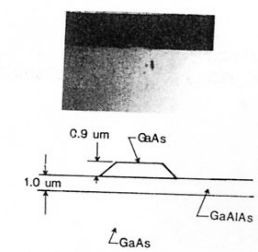

Fig. 2. Photograph showing one of the cleaved end faces of a basic GaAs-GaAlAs single-mode ridge waveguide.

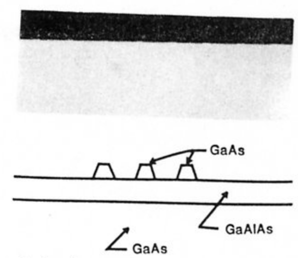

Fig. 3. Photograph showing one of the cleaved end faces of the modulator array.

cutoff voltages of 15, 12.5, and 9 V were measured at 1.06, 1.15, and 1.3 μm wavelengths, respectively, and an extinction ratio or modulation depth or higher than 20 dB has been measured at all wavelengths.

An explanation of the cutoff voltage dependence on the optical wavelength now follows. As indicated in [7], the cutoff voltage is a sensitive function of the refractive index differential Δn, where $\Delta n = n_{eff} - n_s$ in which n_{eff} and n_s designate, respectively, the guided-mode index and

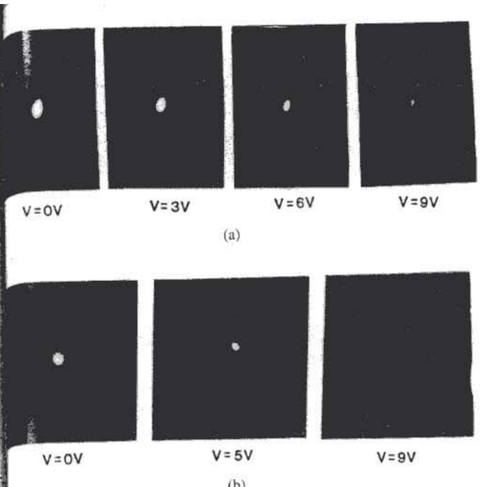

Fig. 4. (a) Output light beam from basic cutoff modulator versus reverse bais voltage at 1.15 μm optical wavelength. (b) Output light beam from basic cutoff modulator versus reverse bias voltage at 1.30 μm optical wavelength.

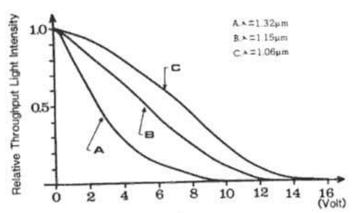

Fig. 5. Measured output light intensity versus reverse bias voltage at three optical wavelengths.

the substrate index. As the guided-mode index approaches the substrate index the scattering loss into the substrate will increase drastically. Now, it is well known from waveguide theory that for a fixed Δn, the longer the optical wavelength, the larger the waveguide thickness needed for guided-mode propagation. In other words, for a given channel waveguide thickness there exists a maximum optical wavelength for support of even the lowest-order mode of guiding. The closer the optical wavelength approaches this maximum, the lower the cutoff voltage.

Fig. 6(a), (b), and (c) show the modulated waveforms of the output light obtained under a 2.2 kHz triangular voltage at 1.06, 1.15, and 1.3 μm wavelengths, respectively. The significant saturation shown in the modulated waveforms of Figs. 6(b) and (c) are consistent with the lower dc cutoff voltages measured at 1.15 and 1.3 μm wavelengths as indicated in Fig. 4.

B. *Modulator Array*

A linear cutoff modulator array that consists of ten identical basic modulators has also been fabricated using the same procedures described in the previous section. The length of the electrode pair and the channel to channel separation were 3.0 mm and 20 μm, respectively, as indicated in Table I. Fig. 7 shows the photograph of the near-field beam profile from seven elements of the array at 1.15 μm optical wavelength, indicating single-mode propagation. Despite the very small channel separation, the optical crosstalk between adjacent channels were measured to be lower than -25 dB at 1.30 μm. This high channel isolation was a result of tight optical field confinement in the ridge waveguides, measured characteristics similar to those with the basic modulator have been consistently obtained. Fig. 8 shows the measured RF response for the elementary modulator of the array at the optical wavelength of 1.06 μm and the reverse bias of -10 V. A bandwidth of 2.5 GHz has been obtained.

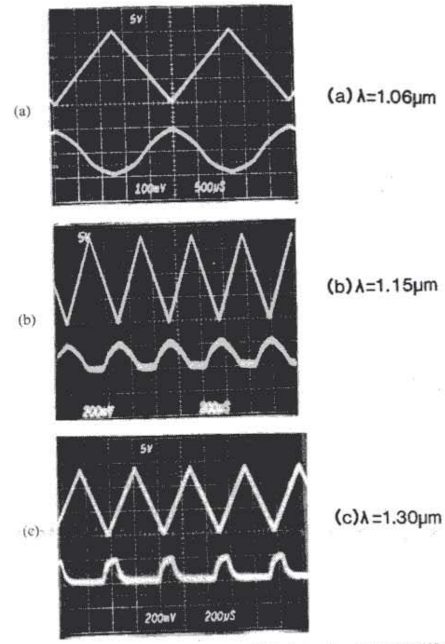

Fig. 6. Modulated waveforms of output light intensity under 2.2 KHz triangular voltage at three optical wavelengths.

Detailed measurement of the frequency response as well as integration of a cutoff modulator array, microlens, array, and planar acoustooptic [13], [14] or electrooptic [15] Bragg diffraction array in a channel-pair composite waveguide structure [14] are being carried out. As in the $LiNbO_3$ substrate [14], the resulting GaAs-based integrated optic modules should find useful application in wideband multichannel communications, computing, and RF signal processing [13], [16]. The detailed results of this continued study will be reported in a separate publication.

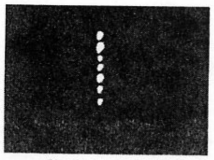

Fig. 7. Near-field beam profile from seven elements of the ten-element GaAs-GaAlAs cutoff modulator array.

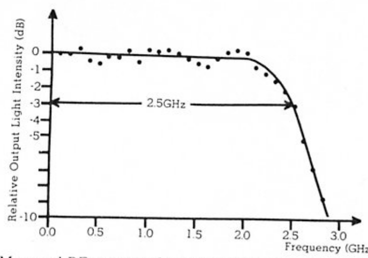

Fig. 8. Measured RF response for one element of the modulator array at optical wavelength of 1.06 μm and reverse bias of -10 V.

V. Concluding Remarks

Single-mode channel waveguide cutoff modulators and cutoff modulator arrays of very high packing density that utilize GaAs/GaAlAs heterostructures together with Schottky barrier contacts are reported for the first time. A high degree of overlap between the modulating electric field and the optical field is achieved as a result of the absence of a buffer layer between the waveguide and the electrode. Therefore, the driving voltage required is significantly reduced. Also, as a result of the relatively thick depletion region and thus smaller capacitance, and very small contact resistance [17], the base bandwidth of such cutoff modulators should be greater than the heterostructure devices that utilize p-n junctions.

The other desirable feature of such heterostructure cutoff modulators is the simultaneous confinement of the single-mode light wave in both vertical and horizontal dimensions of the ridge waveguides used. This feature should facilitate efficient couplings from a light source to the modulator as well as the modulator to an optical fiber. Furthermore, such cutoff modulators can employ both coherent and incoherent light sources as the carrier. This is in contrast to other types of electrooptic modulators such as directional coupler modulator, Mach–Zehnder interferometer, and phase modulator that require the coherent light sources with narrow spectral line width to perform intensity modulation.

Finally, the simplicity in both device structure and fabrication process for such cutoff modulators enables realization of the modulator arrays of very high packing density. In fact, the packing density of 500 per cm realized in this work is the highest that has been reported heretofore.

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References

[1] D. Hall, A. Yariv, and E. Garmire, "Observation of propagation cut-off and its control in the thin optical waveguide," *Appl. Phys. Lett.*, vol. 17, p. 127, 1970.
[2] J. C. Campbell, F. A. Blum, and D. W. Shaw, "GaAs electro-optic channel-waveguide modulator," *Appl. Phys. Lett.*, vol. 26, p. 640, 1975.
[3] D. J. Channin, "Voltage-induced optical waveguide," *Appl. Phys. Lett.*, p. 128, 1971.
[4] O. Mikan and A. Ishida, "Some experiments on a voltage induced optical waveguide," *Japan. J. Appl. Phys.*, vol. 12, p. 1294, 1973.
[5] A. Neyer and W. Sohler, "High speed cut-off modulator using a Ti-diffused LiNbO$_3$ channel waveguide," *Appl. Phys. Lett.*, vol. 35, p. 256, 1979.
[6] P. R. Ashley and W. S. C. Chang, "Improved mode extinction modulator using weakly guided channel waveguide," *Appl. Phys. Lett.*, vol. 45, p. 840, 1984.
[7] R. Chen and C. S. Tsai, "Thermally annealed single-mode proton-exchanged channel-waveguide cutoff modulator," *Opt. Lett.*, vol. 11, p. 546, 1986.
[8] J. C. Baumert, C. Walther, P. Buchmann, H. Haufmann, H. Mekhior, and P. Gunter, "KNbO$_3$ electro-optic induced optical waveguide/cutoff modulator," *Appl. Phys. Lett.*, vol. 46, p. 1018, 1985.
[9] T. Wilson, J. J. Veselka, and J. L. Jackel, "A liquid crystal cutoff modulator for multimode optical waveguides," *Optik.*, vol. 67, no. 1, pp. 37–41, 1984.
[10] A. Yariv, *Optical Electronics*, 3rd ed. New York: Holt, Rinehart and Winston, 1985.
[11] M. W. Austin, "Theoretical and experimental investigation of GaAs/GaAlAs and n/n^+ GaAs rib waveguides," *J. Lightwave Technol.*, vol. LT-2, no. 5, pp. 688–693, 1984.
[12] D. W. Shaw, "Localized GaAs etching with acidic hydrogen peroxide solutions," *J. Electrochem. Soc.*, vol. 118, p. 768, 1971.
[13] C. S. Tsai, D. Y. Zang, and P. Le, "Guided-wave acoustooptic Bragg diffraction in a LiNbO$_3$ channel-planar composite waveguide with application to optical computing," *Appl. Phys. Lett.*, vol. 47, pp. 549–551, Sept. 1985.
[14] C. J. Lii, C. S. Tsai, and C. C. Lee, "Wide-band guided-wave acoustooptic Bragg cells in GaAs-GaAlAs waveguide," *IEEE J. Quantum Electron.*, vol. QE-22, pp. 868–872, June 1986.
[15] D. Y. Zang, P. Le, and C. S. Tsai, "Integrated electrooptic Bragg modulator modules for optical computing," in *Proc. Second Top. Meet. Opt. Comput.*, Mar. 16–18, 1987, Incline Village, NV, Tech. Dig. Series, vol. 11 (OSA) pp. 193–196.
[16] C. S. Tsai, "LiNbO$_3$-based integrated optic device modules for optical communications, signal processing and computing," in *Proc. CLEO '86*, June 9–13, 1986, San Francisco, CA, Tech. Dig., IEEE Cat. No 86CH2274-9, pp. 44–46.
[17] K. Tada, H. Hayashi, M. Tsuchiya, and H. Sakaki, "GaAs AlGaAs DH coupled waveguide optical modulator/switch with Schottky contact," in *Proc. 17th Conf. Solid State Dev., Mater.*, Tokyo, Japan, 1985, pp. 83–86.

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