Gallium Arsenide Integrated Optical Devices
for High-Speed Diagnostic Systems

G. McWright, M. Lowry, E. Takeuchi
G. Murphy, W. Tindall, J. Koo,
and F. Roeske

This paper was prepared for submittal to
SPIE 4th International Symposium on Optical
and Optoelectronic Applied Science and
Engineering, The Hague, Netherlands

March 30-April 3, 1987

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

UCRL--95307

G. McWright, M. Lowry, E. Takeuchi, G. Murphy,
W. Tindall, J. Koo, and F. Roeske

DE87 013107

Lawrence Livermore National Laboratory
P.O. Box 5508
Livermore, California 94550

Abstract

We discuss the design, fabrication, and evaluation of waveguide electro-optic modulators in gallium arsenide for application to high-speed diagnostic systems. We focus specifically on high bandwidth, single event analog modulation, and radiation susceptibility of these devices.

Introduction

Integrated optical circuits have found a wide variety of signal processing applications in telecommunication networks (1). Typically, these devices are employed in high data rate systems, and the research emphasis is thus not on a single event analog modulation. It is only recently that integrated optical instrumentation techniques have been used in diagnostic systems which require analysis of high bandwidth, nonrecurring events (2-3). Furthermore, previous researchers have focused primarily on devices which operate at a wavelength of 1300 nm, because of minimum attenuation for light transmission in optical fibers at this wavelength. This choice of wavelength, however, poses a rather formidable challenge for optical instrumentation applications which require streak cameras to record these single-event, high speed analog signals (4); streak cameras which use photocathodes with an S-20 spectral response typically have good sensitivity at 810 nm but negligible sensitivity at 1300 nm (Figure 1). We discuss the design and fabrication of waveguide electro-optic modulators in gallium arsenide for application to high-speed diagnostic systems. We also focus on the radiation susceptibility of these devices.

Fig. 1: Responsivity and quantum efficiency of typical photocathodes compared to optimum optical fiber operating wavelengths.

Applications

Our application requires the transmission of a single analog signal from a radiation sensor. The simplest way of doing this is to transmit the signal over electrical cable. Unfortunately, electrical cable is lossy and dispersive, so a fast electrical signal will temporally broaden, and useful information is lost. In addition, electrical cable is highly susceptible to radiation. An electrical cable based diagnostic system is thus highly susceptible to radiation induced errors. One way of overcoming this bandwidth limitation is to utilize the high bandwidth capabilities of a photonics diagnostic system. For example, we can use our fast electrical signal to modulate a semiconductor laser diode, send the information over an optical fiber, and record the resulting

MASTER

intensity variations on a streak camera. Even this simple photonics system is less than ideal. When we directly modulate the semiconductor laser diode with a single, fast electrical pulse, the laser oscillates, thus making it difficult to obtain useful data above approximately 3 GHz. For higher speeds, the solution is to use an external modulator in conjunction with a semiconductor laser diode (Figure 2).

Fig. 2: Gallium arsenide integrated optical diagnostic system.

In this case, we apply our electrical signal to a waveguide electro-optic modulator, which effectively encodes the electrical signal information on an optical carrier. The data, as before, are sent over an optical fiber and recorded by a streak camera. We have recently described such a system, based on the electro-optic crystal lithium niobate, which can operate at bandwidths greater than 10 GHz (3). In this paper we focus on waveguide electro-optic modulators fabricated in gallium arsenide for several reasons. First, gallium arsenide can be used to fabricate semiconductor laser diodes, thus leading to the monolithic integration of the laser with the modulator. Second, gallium arsenide integrated optical devices appear to be more radiation resistant than devices fabricated in lithium niobate.

Theory of Operation

Electro-optic waveguide modulators have been built in a number of interesting materials and modulator designs. The insulating electro-optic crystal lithium niobate has the most mature associated technology, and is certainly the material of choice for many system applications.

The semiconductor gallium arsenide offers the potential for true monolithic integration of the laser diode, modulator, and photodetector. However, high waveguide propagation loss and poor electrode contacting to the semiconductor material must first be overcome before electro-optic devices in gallium arsenide reach the same level of technological maturity as comparable devices in lithium niobate. Nevertheless, low loss (attenuation less than 1 dB/cm) waveguides in gallium arsenide have recently been obtained (5), and device bandwidths of greater than 20 GHz have recently been reported (6). The latter design is a phase modulator, and uses the small velocity mismatch between the microwave modulating signal and the propagating optical field in the traveling wave electrode configuration. Of course, Mach-Zehnder interferometers and directional coupler modulators have also been built in gallium arsenide, but the electrical field was applied by means of lumped electrodes. We have focused most of our efforts on high speed directional coupler modulators in gallium arsenide for single event, analog modulation.

A schematic representation of the directional coupler modulator is shown in Figure 3. Ridge waveguides formed in a low doped layer of gallium arsenide are brought in close proximity. Because of the overlap in the optical field tails of the two guides, light couples between them with a coupling efficiency which depends upon the waveguide parameters, wavelength, and interwaveguide separation. For an appropriate device length, all the light entering one waveguide couples to the other. By electro-optically inducing a refractive index change between the two waveguides, the crossover efficiency can be varied; the light intensity is thus modulated.

Fig. 3: Gallium arsenide directional coupler modulator.

Waveguide Fabrication

Ridge waveguides have been used quite extensively in gallium arsenide integrated optical circuits because of their relatively low propagation loss. Schematic representations of the ridge waveguide directional couplers used here are shown in Figures 4 and 5.

The interaction region of the directional coupler, as shown in Fig. 4, consists of two closely spaced ridge waveguides. The coupling between the ridges is a fairly sensitive function of the strip width, w , the gap, G , and the ridge height, h (5). These parameters also affect the single-mode/multi-mode behavior of the waveguides. The single input/double output design was chosen in order to ensure that only one waveguide is excited when light is lens coupled into the structure.

Fig. 4: Gallium arsenide directional coupler waveguides: Top view.

As shown in Fig. 5, our structure consists of a 4 micron lightly doped n layer ($n \approx 10^{14}/\text{cm}^3$) epitaxially grown by MOCVD on a highly doped ($n > 10^{17}/\text{cm}^3$) gallium arsenide substrate. The crystallographic orientation of the gallium arsenide substrate is (100), and all waveguides are patterned along the (110) direction. A large number of ridge waveguide directional couplers were photolithographically defined, and ridges were formed by wet chemical etching the gallium arsenide to the appropriate depth in a buffered sulfuric acid solution. The ridge width, w , height, h , and separation, G , were chosen to ensure single mode operation at a wavelength of 1.3 microns. Typically, w varied from 4.0 to 7.0 microns, and G from 3.5 to 6.5 microns. The ridge height, h , varied from 0.5 to 1.0 microns, and the device length is 6 mm.

Fig. 5: Gallium arsenide directional coupler waveguides: Side view.

Radiation Effects on Directional Coupler Waveguides

The effect of radiation on electronic components has been an active area of interest in the research community for a number of years. For example, Tsui et. al. examined the effects of 35 keV electron beam and ^{60}Co gamma radiation on modulation doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterostructures (8). Their results indicated that while gamma radiation causes no appreciable change in the transport properties of the electron gas, the electron beam cause some mobility reduction without any change in electron density.

The creation of semiconductor optical waveguides by means of ion implantation, ion bombardment, or other lattice damage techniques has also been extensively investigated. In this context, radiation damage of optical waveguides has been investigated. To our knowledge, however, the effects of ^{60}Co gamma radiation on semiconductor directional coupler optical waveguides have not been previously described.

We examined the effects of gamma radiation on both the propagation loss of the structures and the crossover efficiency of the directional couplers. The structures shown in Figs. 4 and 5 were used for the radiation studies. Light from a 1.3 micron laser diode was fiber coupled into the directional couplers, and the crossover was measured by imaging the output of the two channels on a photocathode and determining the relative amount of light in each waveguide. The quasi-TE mode was excited in all cases.

The samples were then irradiated with gamma radiation from a ^{60}Co source, as shown in Figure 6. The source was appropriately filtered so that only 1.18 MeV and 1.33 MeV gamma rays impinged upon the waveguides. The dosage corresponds to 0.39 Roentgen per second, and the samples were exposed for times ranging from 1 to 46 hours.

Fig. 6: ^{60}Co gamma radiation exposure system.

The results are summarized in Tables 1-4, for directional couplers with different W , G , and h . Within experimental accuracy, there is no appreciable change in the crossover efficiency, before and after sample irradiation. No change in propagation loss was noted. Presumably then, any radiation effects occur on a much shorter time scale, so "in situ" monitoring of the samples may be necessary. The crossover efficiency of many of the directional couplers appears to be anomalously close to 50 percent, which indicates that we may be exciting a continuum of modes within the waveguide structure. Nevertheless, the crossover efficiency is quite repeatable and does not change before and after sample irradiation.

Table 1

$G = 5.0$ micron
(1 hour exposure time, $h = 0.5$ micron)

$W = 4$ micron	$G = 5.0$ micron	Crossover	
		Before	After
	5.5	0.57	0.51
	5.75	0.49	0.51
	6.5	0.55	0.52
		0.53	0.51

W = 5 micron	G = 3.5 micron	0.52	0.52
	3.75	0.53	0.51
	4.25	0.53	0.53
	4.5	0.54	0.54
	4.75	0.55	0.54
	5.0	0.53	0.61
	5.5	0.55	0.44
	6.0	0.54	0.56
	6.25	0.56	0.60

Table 2

GaAs 7
(7 hour exposure time, h = 1.0 micron)

		Crossover	
		Before	After
W = 4 micron	G = 3.5 micron	0.51	0.48
	3.75	0.49	0.49
	4.0	0.52	0.50
	4.5	0.54	0.52
	4.75	0.50	0.51
	5.0	0.56	0.57
	5.5	0.61	0.59
	6.0	0.68	0.66
	6.25	0.65	0.65
W = 5 micron	G = 3.5 micron	0.48	0.47
	3.75	0.52	0.48
	4.0	0.56	0.52
	4.25	0.58	0.61
	4.5	0.63	0.64
	4.75	0.75	0.76
	5.5	0.75	0.73
	6.25	0.78	0.77
W = 6 micron	G = 3.5 micron	0.60	0.43

Table 3

GaAs 22
(22 hour exposure time, h = 0.5 micron)

		Crossover	
		Before	After
W = 6 micron	G = 3.5 micron	0.60	0.51
	3.75	0.56	0.53
	4.5	0.60	0.55
	4.75	0.60	0.55
	5.0	0.61	0.59

Table 4

GaAs 46
(46 hour exposure, h = 0.5 micron)

		Crossover	
		Before	After
W = 4 micron	G = 3.5 micron	0.51	0.51
	3.75	0.59	0.60
	4.25	0.51	0.46

Electro-Optic Characterization

We have recently fabricated a traveling wave directional coupler modulator in gallium arsenide. Here, we report preliminary electro-optic measurements on the device.

A schematic representation of the directional coupler modulator is shown in Figure 7. The device consists of two ridge waveguides, with an interaction region $L = 6$ mm. The ridge waveguides were formed by wet chemical etching a 4 micron thick n -GaAs layer. The step height $h = 0.5$ micron, and the substrate is a n -GaAs wafer. The strip width $w = 4$ micron, and gap, $g = 5.5$ micron. The single input/single output design was chosen to facilitate lens coupling.

Fig. 7: Schematic representation of traveling wave directional coupler modulator

Because the epitaxial layer is moderately conductive, some means of electrical isolation between the "hot" electrode and ground plane must be provided. A plasma enhanced chemical vapor deposition system (PECVD) was used to deposit a 2000 Å isolation layer.

We then photolithographically defined and patterned traveling wave coplanar electrodes on the directional coupler waveguides. The asymmetric electrodes have a strip width $W = 16.5$ micron and gap, $G = 5.5$ micron. The gold electrodes were electroplated to a height of 2.5 microns.

The device was suitably packaged, and preliminary DC switching characteristics are shown in Figure 8.

Fig. 8: DC switching characteristics.

The DC switching characteristics were measured by end-fire coupling 1.3 micron laser light into the ridge waveguide. The quasi-TE mode was excited in order to make use of the r_{41} component of the electro-optic tensor, and the applied DC voltage was varied from -10 to +10 volts. We are presently investigating the pulse characteristics of the device.

Conclusions

In summary, we have described a gallium arsenide integrated optical diagnostic system for the remote measurement of high speed transient signals. Our radiation susceptibility studies indicate that there is no appreciable change in waveguide characteristics (transmission or crossover efficiency) for long term gamma ray exposure. Furthermore, preliminary electro-optic measurements indicate that our traveling wave directional coupler modulator has a DC switching voltage of approximately 10 volts. Pulse characteristics and actual system implementation of the modulator are forthcoming.

Acknowledgments

The support and encouragement of J. Salch and W. Slivinsky is gratefully acknowledged. D. Redhead assisted with the radiation measurements, and his help is also noted. The work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

REFERENCES

1. R. C. Alferness, "Waveguide Electro-Optic Modulators," IEEE Trans. Microwave Theory and Techniques, MTT-30, pp. 1127-1137 (1982).
2. G. M. McWright, D. R. Jander, J. C. Koo, P. Kwiat, M. E., Lowry, F. Roeske, and V. W. Slivinsky, "Waveguide Electro-Optic Modulators for High Speed Diagnostics," Proc. SPIE, 612 (1986).
3. F. Roeske, M. Felt, J. Fleck, D. Jander, B. Kidd, J. Koo, M. Lowry, G. McWright, and W. Tindall, "Directional Coupler Modulators Designed for Analog Modulation of Large Signals at 810 nm," Proc. SPIE, 720 (1987).
4. M. E. Lowry, M. D. Rotter, and D. R. Jander, "A Means of Extending Streak Camera Recording into the Important 1300-1600 nm Wavelength Regime: Parametric Frequency Upconversion," Proc. SPIE, 497, pp. 29-33 (1984).
5. H. Inoue, K. Hiruma, K. Ishida, M. Sato, and H. Matsumura, "Switching Characteristics of GaAs Directional Coupler Optical Switches," Applied Optics, Vol. 25, pp. 1484-1490 (1986).
6. S. Wang, S. Lin, and Y. Hwang, "GaAs Traveling Wave Electro-Optic Waveguide Modulator with Bandwidth > 20 GHz at 1.3 Microns," OFC/IOOC Technical Digest, Paper WK3 (1987).
7. F. J. Leonberger, J. P. Donnelly, and C. G. Bozler, "GaAs pⁿn⁺ Directional-Coupler Switch," Applied Physics Letters, Vol. 29, pp. 652-654 (1976).
8. D. C. Tsui, A. C. Gossard, and G. J. Dolan, "Radiation Effects on Modulation-Doped GaAs-Al_xGa_{1-x}As Heterostructures," Applied Physics Letters, Vol. 42, pp. 180-182 (1983).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.