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INTEGRATED OPTICS FOR ARMY FIRE CONTROL SYSTEMS

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20. ABSTRACT (Continued)

Ion implantation of doped semiconductor substrates is a highly promising technique for the fabrication of individual optical components as well as monolithic integrated circuits. Since Army requirements demand lower carrier frequencies, the use of ion implantation to form infrared guided wave devices is discussed. Prior work in this area is summarized, and basic problems relating to the formation of infrared optical components are identified. Results of wave-guiding of a helium neon laser beam in thin aluminum oxide films are presented as preliminary experimental procedures to be followed in the infrared.

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INTRODUCTION

Integrated optics is a research area that has developed in the past ten years into a major technology with tremendous potential for both civilian and military sectors. This technology includes the fabrication of guided wave components and the integration of these devices into sensing and signal processing circuits. While this technology is usually referred to as integrated optics, the guided wave devices and circuits are not restricted to operation at visible frequencies, but can be made to operate at other frequencies in the electromagnetic (EM) spectrum.

Guided wave or optical devices are the analogs of the familiar electronic devices such as cables, waveguides, modulators, switches, sources, and detectors that rely on the motion of electrons and their subsequent deflection. However, optical devices guide an EM wave through a material structure and function directly on the propagating wave. Because of the higher carrier frequencies of optical waves, the information that guided wave devices can process is nearly 10,000 times greater than that of electronic devices. Also, these optical devices are several orders of magnitude faster than their electronic counterparts. Other advantages of guided wave devices include lower transmission losses, virtually complete immunity to EM interference and countermeasures, and the elimination of the use of strategic materials such as copper. Once these devices are integrated into optical circuits, additional benefits of greater reliability and durability will accrue.

The development of integrated optical circuits parallels very closely the development of integrated electronic circuits. First, discrete electronic elements such as transistors, capacitors, and oscillators were used. This corresponds with the use of discrete optical elements such as lenses, prisms, and lasers in current optical systems. Later, the discrete electronic devices were assembled into circuit boards and, eventually, into monolithic integrated circuits. Similarly, the goal of integrated optics is to miniaturize and assemble the discrete optical elements and devices into a monolithic circuit of a few square millimeters in area. This size reduction of optical systems is even more dramatic than what has been accomplished in the electronics area.

OPTICAL WAVE GUIDES

Theory

The basic component in an integrated optical circuit is the waveguide. This structure serves to confine the EM wave to a particular

region and to specify the direction of propagation of this wave. The operation of a planar (two-dimensional) waveguide is illustrated in figure 1. In this figure, the assumption is that the EM wave has already been introduced into the waveguiding region. This can be accomplished through various methods including end-fire coupling, prism coupling, or even light generation in the waveguide. The waveguide in this figure is formed by the middle region identified by its optical index of refraction, n_f . The regions above and below the waveguide are similarly labeled by their indices n_o and n_s . For the EM wave to be guided in the middle region, n_f must be larger than either n_o or n_s . When this condition is satisfied, an angle of incidence exists at each interface, called the critical angle, below which the incident wave will be totally reflected. The guided wave will then propagate in a zig-zag fashion undergoing total internal reflection at each interface. Upon each reflection, the EM wave will undergo a change in phase. For the propagating wave to be guided, these phase changes, in addition to the phase change resulting from the optical path difference, must add constructively. This leads to an eigenvalue equation by which the number of discrete modes are determined that can propagate in the waveguide. In the case of lossless media, this eigenvalue equation is relatively simple and is shown in figure 2 where t is the thickness of the waveguiding region, θ_f the angle of propagation of the guided wave in the film, λ_o the wavelength of the EM wave in free space, and Φ_{fo} , Φ_{fs} the phase changes due to reflection at the respective interfaces.

These phase changes can be calculated from the Fresnel reflection coefficients for a planar interface and are different for the two states of polarization. Therefore, for a given optical waveguide, two eigenvalue equations exist, one for each polarization by which the propagating waves are determined. The guided modes in a planar waveguide are usually denoted TE_j and TM_j with $j = 0, 1, 2, \dots$; TE refers to transverse electric (parallel polarization); TM is transverse magnetic (perpendicular polarization); and j is the modal order. The eigenvalue equation can be solved graphically to determine the number of guided modes for a given value of the waveguide thickness. The resulting set of curves for a particular choice of optical indices is shown in figure 3. As can be seen in this figure, the curves corresponding to different modal orders are widely separated as compared with curves of the same modal order but different polarization. This means that the propagating modes of the same order normally occur in doublets, one for each polarization, and are distinct from the doublet for the next order. These curves can also be used to determine the thickness of the planar waveguide provided the angles of the propagating modes have been identified and the optical indices are known.

While the description of modes in a channeled (three-dimensional) optical waveguide is more complicated, the same concepts of total internal reflection and constructive interference apply. The guided

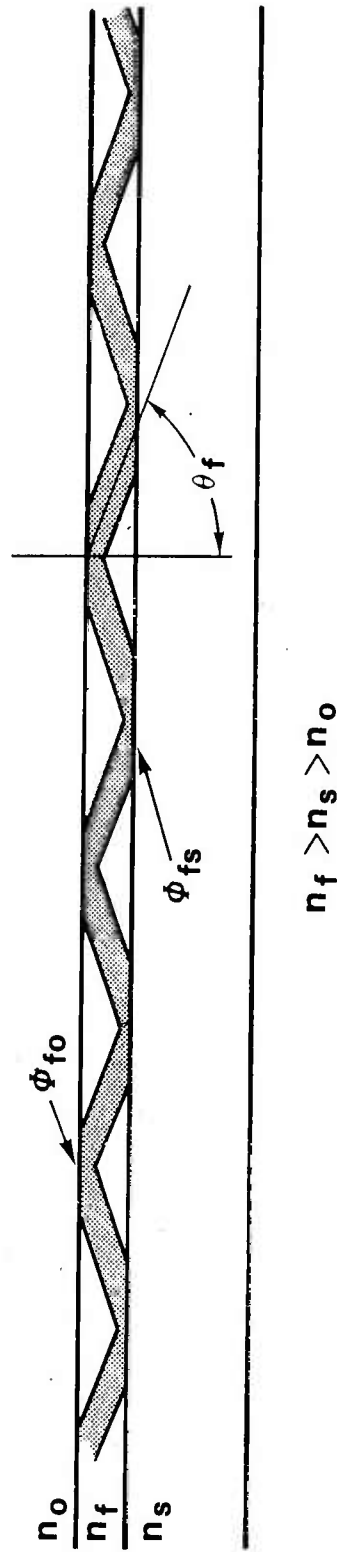


Figure 1. Planar optical waveguide.

$$2k n_f t \cos \theta_f - 2\phi_{f0} - 2\phi_{fs} = 2m\pi$$

$$k = \frac{2\pi}{\lambda_0} ; \quad m = 0, 1, 2, 3, \dots$$

S Polarization (TE Modes)	P Polarization (TM Modes)
$\tan \phi_{fi} = \frac{(n_f^2 \sin^2 \theta_f - n_i^2)^{1/2}}{n_f \cos \theta_f}$	$\tan \phi_{fi} = \frac{n_f^2 (n_f^2 \sin^2 \theta_f - n_i^2)^{1/2}}{n_i n_f \cos \theta_f}$

Figure 2. Planar waveguide eigenvalue equation.

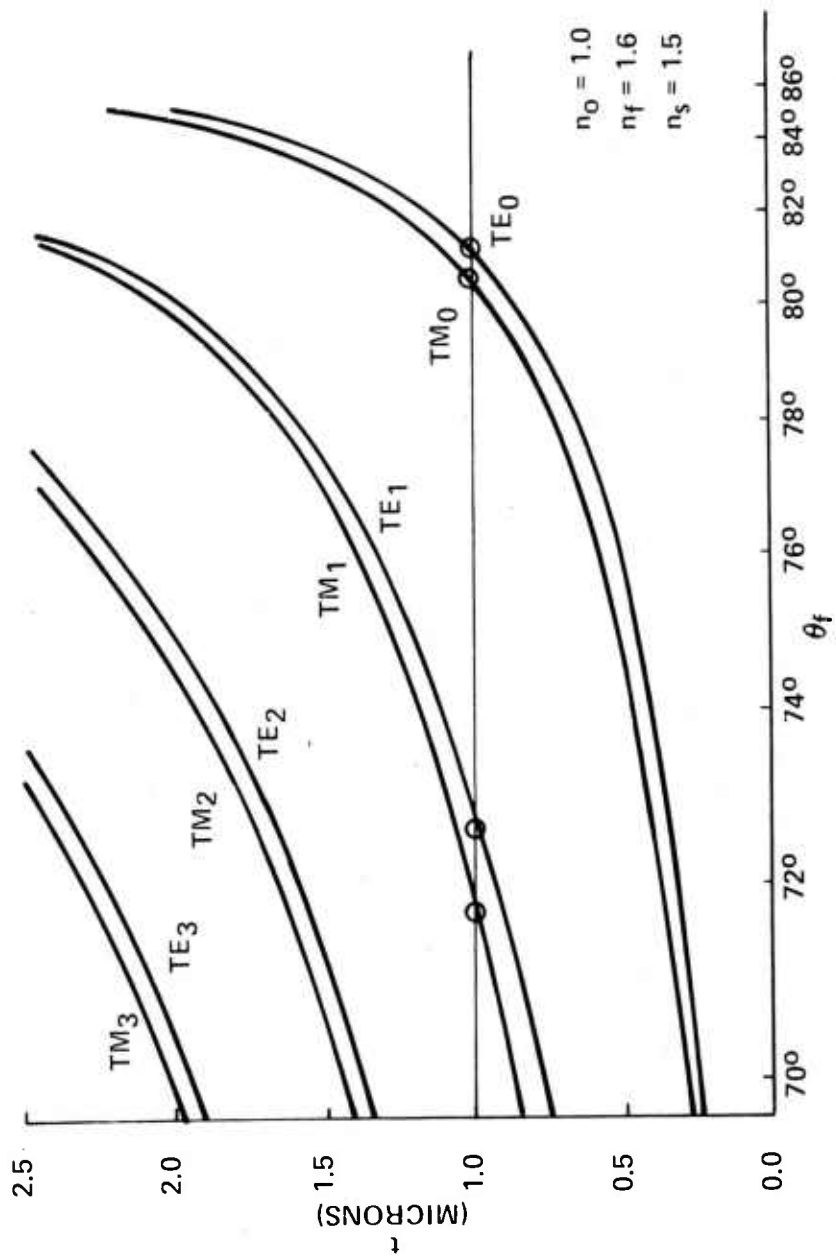


Figure 3. Predicted waveguide modes.

modes in this case are specified TE_{jk} and TM_{jk} with two modal numbers j and k now being required. Channeled waveguides are the structures that will be required in integrated optical circuits. In such circuits, the guided wave will be switched, coupled into other waveguides, polarized, filtered, modulated, and eventually converted into electrical signals. This processing and conversion is more efficient in channeled waveguides and represents the basic operation of an optical circuit.

Experimental Procedures

In the fabrication of optical waveguides, the design of the waveguiding structure and the values of the optical indices of the waveguiding region and the surrounding media are of paramount importance. Various methods have been tried. Some of the principal methods include thin-film deposition, epitaxial growth, filled channel and embossed techniques, diffusion, and ion implantation. The materials that have been used range from glasses to halides to semiconductors. In this report, work with thin-film waveguides will be described and the current efforts in ion implantation will be indicated.

During the past fiscal year, thin-film aluminum oxide waveguides were fabricated and studied. These planar waveguides were prepared by electron beam evaporation of aluminum oxide in the Thin Film Laboratory of the Fire Control Division. The thin films were deposited on glass slides and had a thickness of approximately one micron. To demonstrate waveguiding in these structures and to measure the propagating mode, an optical experimental setup (figure 4) was assembled. This facility comprises a Helium Neon (HeNe) laser source (0.6328 micron), a beam collimator, focusing lenses, and a stage that holds the planar waveguide and that is situated on a rotary table. Introduction of the laser light into the thin film was accomplished by means of prism coupling. A schematic drawing of this coupling technique and the resulting waveguiding is included as figure 5. A collimated HeNe laser beam impinges on the glass prism at an incident angle θ , is refracted by the prism, and at certain distinct angles couples into the waveguide. The rotary table allows the incident angle to be varied until waveguiding is achieved. When coupling occurs, the slide flashes with the red HeNe light and displays a pattern similar to that shown in the top view of figure 5. While the film was highly transparent at this wavelength (transmission was nearly 97 percent), the film did contain inhomogeneities and surface roughness by which light was scattered out of the waveguide. This scattering is responsible for the flame-like pattern. For a perfect film, the waveguided light would be visible only at the end of the film where it would be coupling back into the air. A photograph of such a coupling event in one of the films is included as figure 6. For each of the thin-film waveguides, the polarization and the coupling angle for the propagating modes were measured. These data were used to determine the thickness of the film

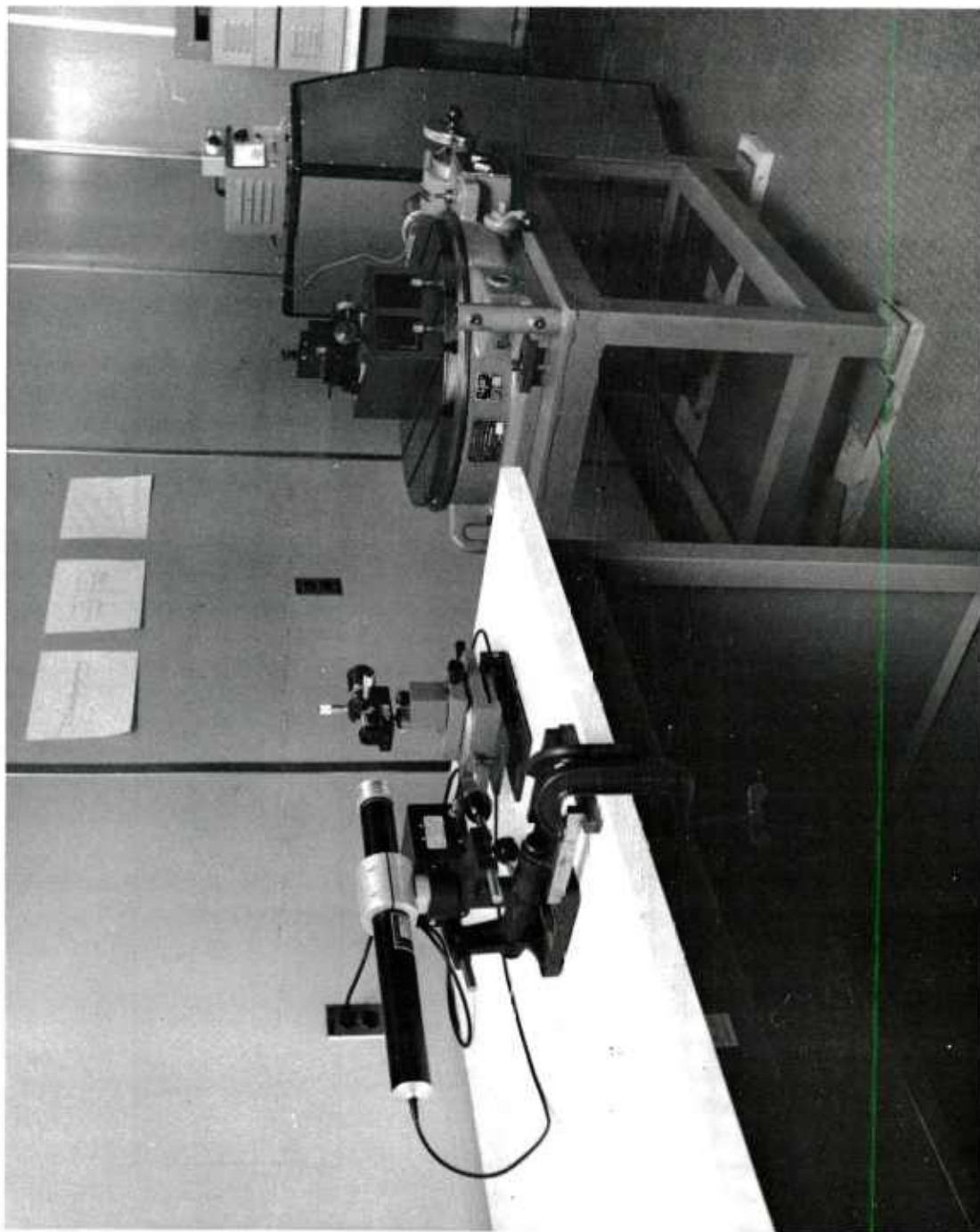


Figure 4. Experimental facility.

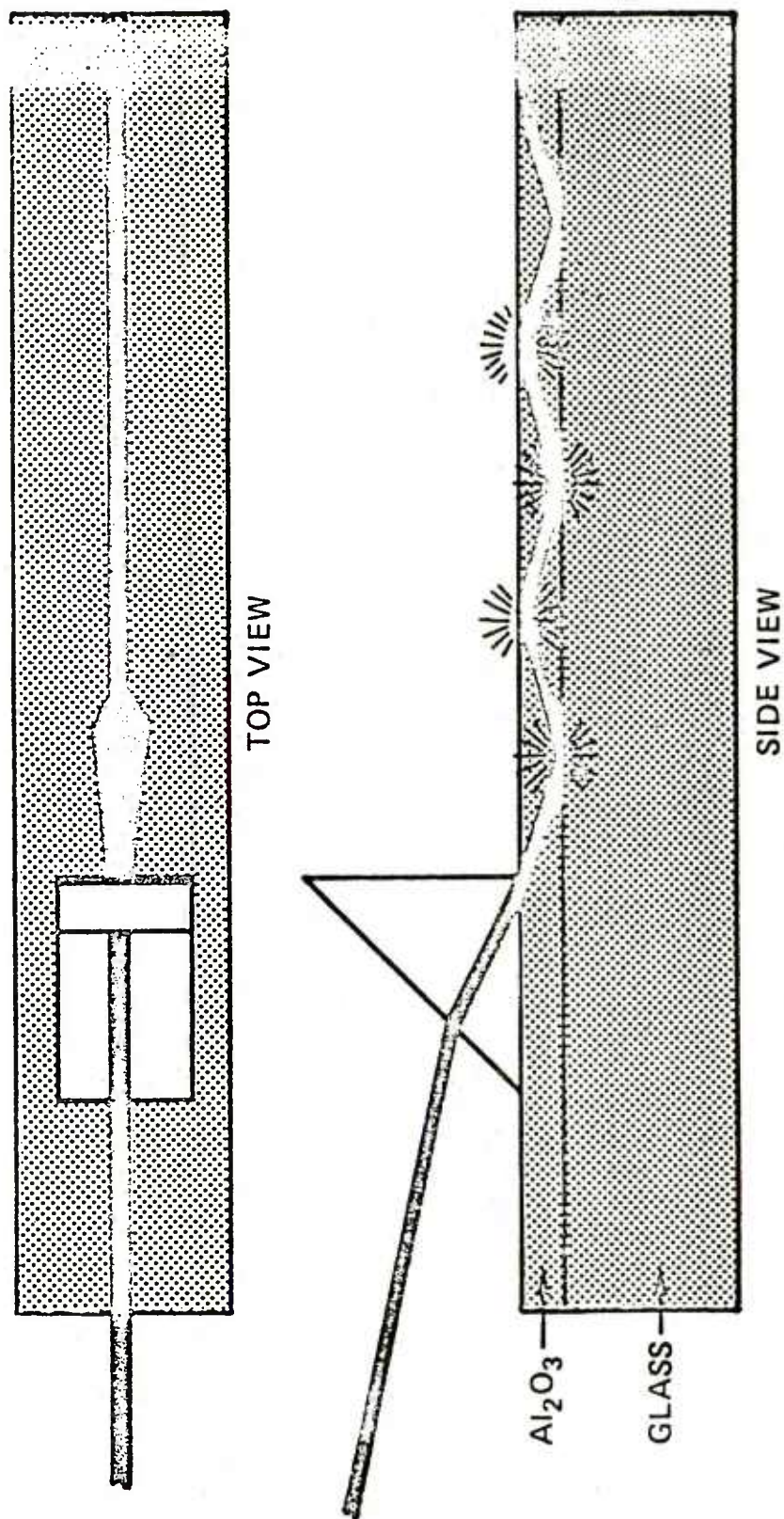


Figure 5. Prism coupling technique.

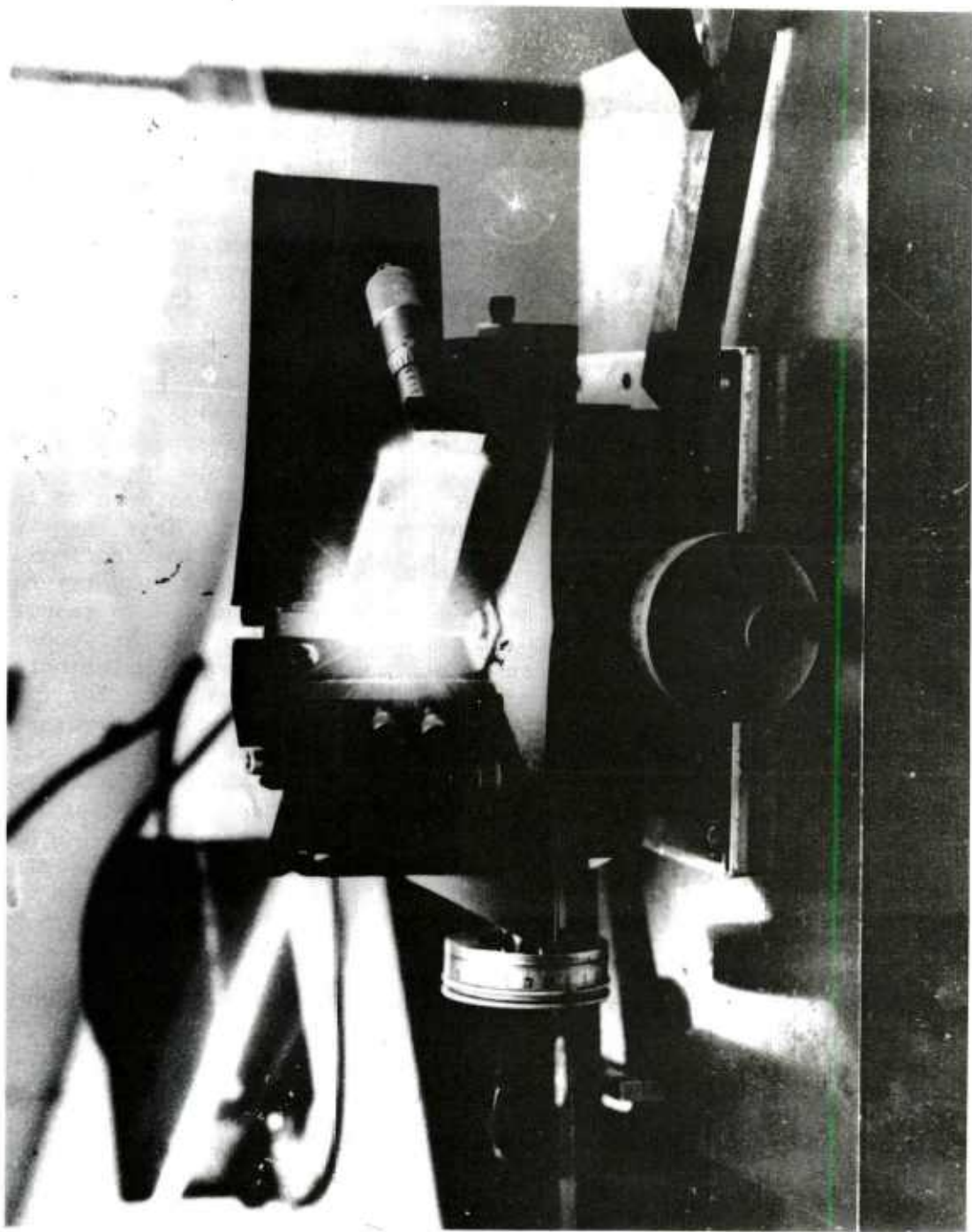


Figure 6. Laser coupling into thin-film waveguide.

and its optical index by means of the eigenvalue equation shown in figure 2.

Another technique, called the method of "M Lines," was also used to examine the waveguiding properties of the thin films. In this technique, illustrated in figure 7, the prism is rotated 90 degrees so that its hypotenuse is in contact with the film. The laser beam is refracted by the prism and couples into the waveguide as in the previous method. However, the beam is now focused at the prism/waveguide interface and presents a band of incident angles available for coupling into the film. If the polarization of the laser beam is adjusted to contain both parallel and perpendicular components and if the band of angles includes one or more mode coupling angles, then the following situation is observed: Light is refracted into the prism, strikes the prism/waveguide interface, and is almost totally reflected. The reflected light, when viewed on a screen in the far field, appears to contain one or more dark lines. Each dark line corresponds to a particular angle, within the incident band, that is a solution of the eigenvalue equation. Light incident at these angles has coupled into the waveguide and is missing from the reflected beam. This light will be guided a short distance in the film where, due to imperfections such as inhomogeneities, roughness, and thickness variations, a portion of it will be converted into the other modes of the film. As a result of this conversion, once a particular mode is excited, all other modes will likewise be excited. These guided modes are soon coupled out of the film by the prism and refracted toward the screen. The far field pattern comprises a series of bright lines with each line corresponding to a particular guided mode. The intensity of these lines is greatly reduced in comparison with the reflected beam. Still, the M Lines are discernible and the technique simultaneously allows observation of the set of guided modes. Figure 8 is a photograph of the M Lines with the use of the same thin-film waveguide shown in figure 6. To photograph the bright lines, a stack of neutral density filters was used to reduce the intensity of the reflected beam. This set of filters appears in the photograph (figure 8) as the square dark area inclosing the reflected beam spot. The dark horizontal line running through the photograph is the wire by which these filters were supported.

These experimental techniques are important since they permit demonstration of optical waveguiding and identification of the guided modes. Often in the fabrication of optical waveguiding structures with novel geometrical designs or new material combinations, it is not known a priori whether optical waveguiding will be achieved and, if so, what the guided modes will be. These techniques are then required and can be performed even at wavelengths outside the visible spectrum.

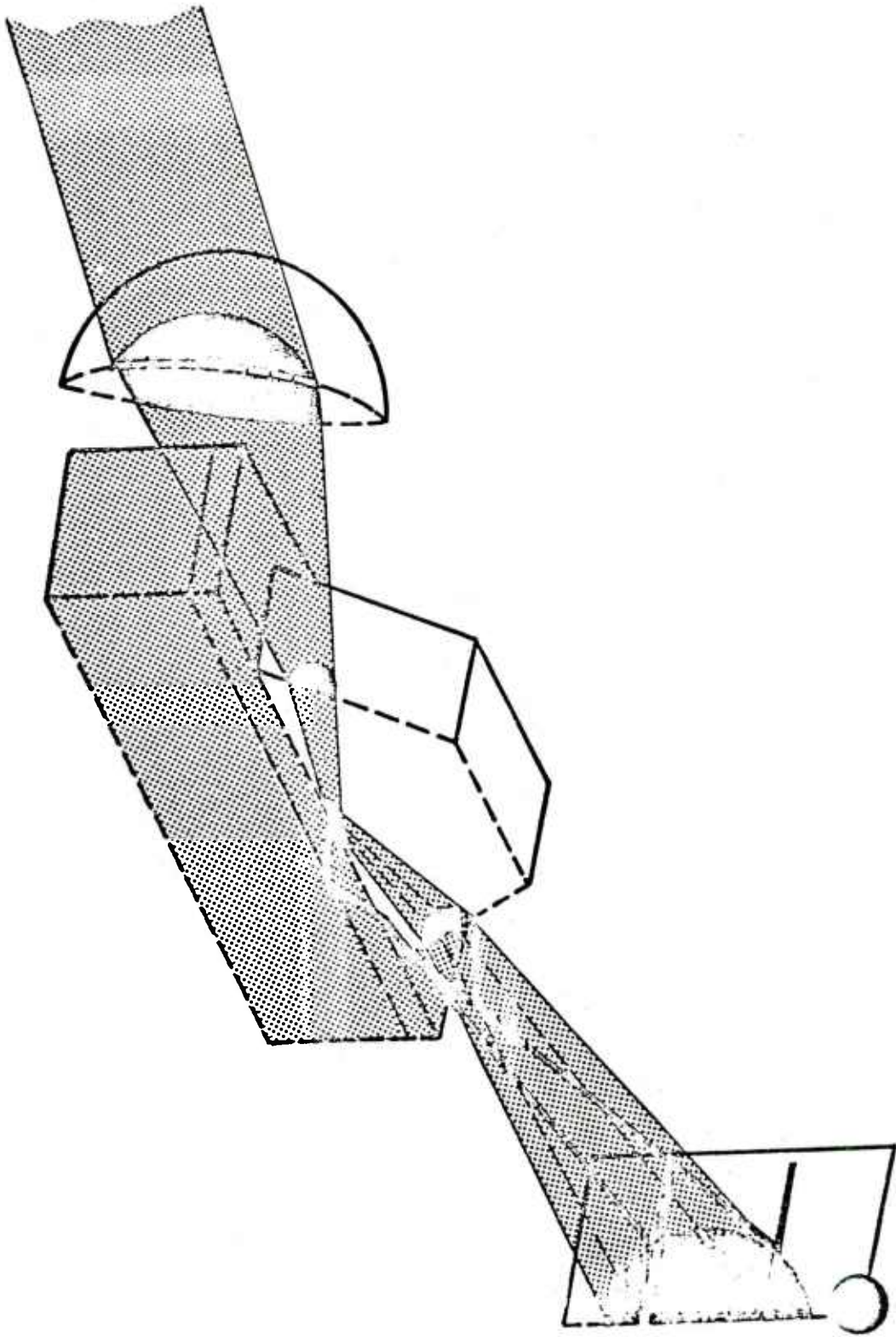


Figure 7. Method of M Lines.

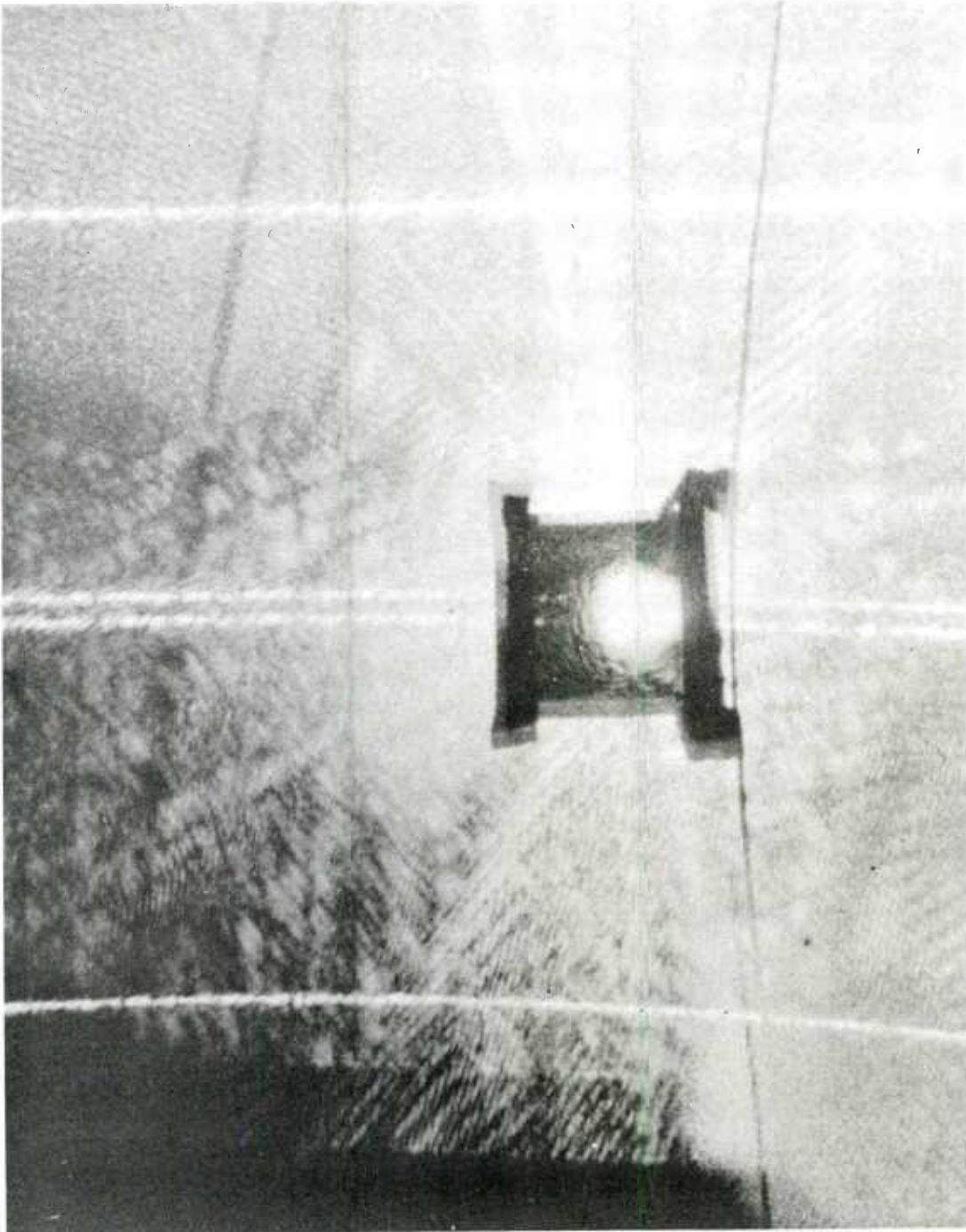


Figure 8. Photograph of M Lines.

Ion Implantation

The use of integrated optical circuits in Army fire controls systems is dependent upon requirements for these systems that are imposed by anticipated military scenarios. Because of the requirement for 24-hour/all-weather operation, the Army has been emphasizing systems that operate at longer wavelengths, particularly in the infrared and millimeter wave (MMW) regions. Active devices such as CO₂ lasers and MMW transmitters form a natural basis for the application of integrated optics to Army fire control.

In the present effort, ion implantation is being investigated for the fabrication of guided wave devices compatible with CO₂ laser systems. Ion implantation is the process in which atoms are ionized, accelerated through a potential difference, and strike a suitable material target. The resulting damage in the material and the introduction of foreign atoms can produce electronic, chemical, and optical changes. In fact, ion implantation is the major production technique used in the electronics industry for the manufacture of integrated electronic circuits. The primary advantage of this technique lies in the precise, external manner by which doping of materials can be controlled. Any ion species can be introduced into a given material and the dopant concentration will not be limited by ordinary solubility considerations. The dosage can be monitored very accurately and the depth profile of the implanted ions can be controlled by adjustment of the energy of the accelerator. This permits realization of dopant profiles that could not be achieved by diffusion or any other technique. Also, implantation of materials can be performed over a wide range of temperatures that allow for minimal lateral spread of the dopant ions. This technique is a relatively simple procedure that is compatible with modern masking methods to achieve special configurations of the doped regions. Additionally, the possibility exists that entire optical circuits can be "written" directly on a chip without the use of masks.

While ion implantation has been used to fabricate guided wave components at visible and near infrared wavelengths, little effort has been directed toward the application of this technique to form guided wave devices in the far-infrared wavelengths. Lincoln Laboratories has made low-loss waveguides at 10.6 microns through proton implantation of Cadmium Telluride. However, a drawback to this work is the very high accelerating energies, over 1 MeV, that were required. Accelerating machines capable of such large energy outputs are not readily available and are very costly to operate. If low-loss infrared waveguides could be fabricated with moderate energy accelerators (less than 300 keV), then ion implantation would be established as a prime fabrication technique for integrated optics in this spectral region.

This is the task that is being addressed in this current research effort: to determine the feasibility of fabricating infrared waveguides by ion implantation of compound semiconductor wafers. Semiconductor materials were selected for this work because all major functions of an optical circuit such as light generation, waveguiding, modulation, and detection can be achieved on these materials. Consequently, semiconductors hold the potential of being used to form monolithic integrated optical circuits. Several technical barriers exist that need to be remedied before this goal can be realized. First, penetration of the optical changes in the target wafers must be deep enough to allow for waveguiding at 10.6 microns. With moderate energy accelerators, the implanted ions reach only a depth of 2-3 microns. However, the optical effects do not always coincide with the dopant profile. Through enhanced diffusion, these effects may penetrate to sufficient depths for infrared waveguiding. Also, the magnitude of the optical changes in the wafer must be large enough to confine most of the energy of the guided wave to the implanted region. Otherwise, a large portion of the guided mode will extend beyond the waveguide and may interact with other structures on the wafer leading to losses and spurious signals. Finally, the major criterion for the fabricated waveguides is that they should be characterized by low losses on the order of 2-3 dB/cm. Even though the envisioned optical circuits are to be contained on a chip, with an area of a few square millimeters, larger losses in the waveguides cannot be tolerated.

CONCLUSIONS AND RECOMMENDATIONS

With the development of infrared integrated optical circuits, a wide range of applications would be found for them in future Army fire control systems. Typical CO 2 systems in which these circuits could be used include laser radars, miss distance sensors, (MSD), Cannon-Launched Beam Rider Projectiles (CLBRP), and smart munitions. In the laser radar, infrared optical circuits can be used together with infrared optical fibers to perform phased array transmission, heterodyne detection, and parallel processing of received signals. Similarly, for the MSD, these circuits can provide heterodyne detection of the reflected signals and can be used to form a miniature laser transmitter on the shell. With the CLBRP, such circuits can perform laser beam encoding of these signals aboard the projectile. For smart munitions, optical circuits can be used to form laser transceivers that will locate and identify potential targets by correlation of received signals with known target signatures.

These possible applications are only a few of the cases in which integrated optics can improve the performance of Army fire control systems. Other applications are likely to arise as further use is made of this technology. Similarly, integrated optical circuits, with their

greater bandwidth and faster operation are expected to play an increasingly larger role in helping the Army meet its future fire control requirements.

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