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LASER BEAM STEERING WITH SEMICONDUCTOR WAVEGUIDE

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ABSTRACT

The ability to rapidly and randomly steer a laser beam is critical to the success of free-space satellite-based laser "radar" systems for missile defense and target tracking. By applying waveguide technology, Spire will demonstrate multi-dimensional, all-electronic laser beam steering. Parallel arrays of electronically phase-modulated waveguide structures are being fabricated, and a metal grating has been designed to spatially dissect an incident coherent planar waveform, emitted at 1059 nm by a Nd:YAG laser. The rotation of the output light-beam will occur through constructive interference effects in the far field. A two dimensional array of phase-control channels would allow scanning the beam over the entire image plane.

Initial efforts in Phase I are being focused on fabrication and testing of a two channel, vertically situated set of buried waveguides. The implementation of a double-buried semiconductor structure with two GaAs cores and $Al_xGa_{1-x}As$ cladding has been analyzed in detail to determine materials parameters that would allow us to demonstrate the highly novel concept of high speed, electronic laser steering of a laser beam in the vertical direction. The GaAs waveguide is being grown to contain a pn junction, while the cladding consists of $Al_{0.08}Ga_{0.92}As$, with the lower cladding doped n-type, and the upper cladding doped p-type. For a 2 micron thick waveguide, only the fundamental mode and perhaps the first harmonic can be supported, which should allow demonstration of optical interference in the far field.

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1 INTRODUCTION

1.1 Background for Laser Beamsteering

There is increasing interest from SDIO in using laser sources for free-space satellite-based laser radar sensors which allow range and velocity determinations for target identification and tracking. In all cases, agility in redefining the direction of propagation of the laser beam, both rapidly and randomly, is a critical systems requirement. Traditionally, the trajectory of a laser beam is controlled by some mechanical means, such as a finely threaded screw for x-y positioning, or a moveable mirror for angular steering, as discussed recently by Foreman and LeClair.¹ Such mirrors may be rotated by a conventional motor, or may be configured as part of a galvanometer.² Note, however, that a gaussian lightbeam with emitting aperture size $w_0 = 2.5$ mm will diverge at an angle of only 100 μ rad, and fine control of the position of such a beam with a gimbaled mirror over any significant distance can pose a very difficult task. It is also possible basically to steer the beam by mechanical translation of a lens, especially by using piezoelectric elements to move arrays of microlenses.³ However, various mechanical positioners typically suffer from excessive rotational or translational inertia and friction effects, which makes them inherently slow; additionally, they may not be robust enough to survive hostile environments, such as those encountered in space applications (where repairs are virtually impossible).

It would be extremely beneficial to develop an all electronic device which would be capable of repositioning a laser beam in a nanosecond time-frame. For example, this would allow constructing a laser radar that could monitor a large number of targets simultaneously; or providing communications links between a set of space-based battle platforms that could shift among them without the need for buffering the data, as well as maintain tracking lock without loss of information due to beam wander.

Very fine and extremely rapid lightbeam positioning should be possible through the electronic control of the dynamic optical properties of a waveguide. For example, the thermo-optic effect basically functions by creating a vertical temperature gradient in a waveguide material, thereby causing a gradient in refractive index, and hence effectively forming a prism. With a temperature gradient of 175°C, a deflection of 1° is possible in glass, but deflections as large as 10° are possible with other materials having larger temperature coefficients of refractive index, such as PLZT. Unfortunately, the response times of these devices is determined by the rise and fall times of the surface temperature, which will be in the millisecond range, and thus rather slow. It is not easy to imagine how two dimensional steering could be implemented with this effect. Thus novel approaches to this problem would be welcome.

1.2 Approach to Technology Development

An all electronic beam steering system can be envisioned based on the principles of phased array radars. Here, the laser wavefront must be dissected into several parallel components using a transmission grating. Each component is then passed through a series of parallel waveguides. The process then relies on altering the index of refraction of each waveguide through which the components of the laser beam are travelling, and hence providing a controlled phase retardation $\Delta\phi$ in each guide. There are several known electro-optic effects, viz., the Linear

Electro-Optic Effect (LEO or Pockels Effect), the Electro-Refractive Effect (Franz-Keldysh Effect), the Free Plasma Effect, and the Band Filling Effect (Moss-Burstein Shift),⁴ all capable of providing phase shifting. Most of these effects are very significant for wavelengths of light near the semiconductor's band gap energy. Undoubtedly, these effects provide the greatest promise for achieving high speed electronic beam steering. It is the intent of the present program to choose a materials system which offers the utmost flexibility in exhibiting the desired phase shift for steering the Nd:YAG solid-state laser. Based on our modelling of the waveguide system, we are concentrating our efforts on the GaAs/Al_xGa_{1-x}As system.

1.3 Summary of Initial Results

We recognized that beam steering is the result of optical interference between adjacent lightwaves, and therefore that the waveguide should support only a single (fundamental) operating mode, to prevent the occurrence of spurious extraneous interference patterns between competing modes. The results of our calculations have caused us to reject the Si/SiO₂ system because of physical size limitations. All efforts are now directed to GaAs/AlGaAs. This materials system appears to make the most sense for steering the 1059 nm Nd:YAG laser. These materials are basically transparent at the wavelength of the laser, and simultaneously feature all four electro-optic effects which were mentioned above.

2 RESULTS

2.1 Formation of Buried Waveguide Layers

The AlGaAs/GaAs waveguide was designed as follows. A pn junction will be grown symmetrically in each GaAs waveguide. By applying a reverse bias across a diode, the free charges can be depleted, leading to a change in the refractive index.⁵ The dependence of the depletion width in a GaAs junction diode under reverse bias is shown in Figure 1.⁶ According to this figure, we have chosen a doping concentration for our diodes of $4 \times 10^{16} \text{ cm}^{-3}$, to allow depletion across the entire 2 micron guide with an applied reverse bias.

To calibrate the system, we grew AlGaAs layers with the maximum Ga/Al ratio that is possible in the reactor that is being used to grow the waveguides. Recall from Progress Report #2 that we were aiming for about 2% aluminum concentration. This concentration proved to be below the limit of the Al flow controller. The photoluminescence spectrum of the best sample is shown in Figure 2. With the emission peak at 810 nm, we calculated an aluminum concentration of 7.7%. Therefore, we undertook a calculation of the dependence of the number of guided modes in a waveguide with thickness of the guide and refractive index of the cladding as parameters.

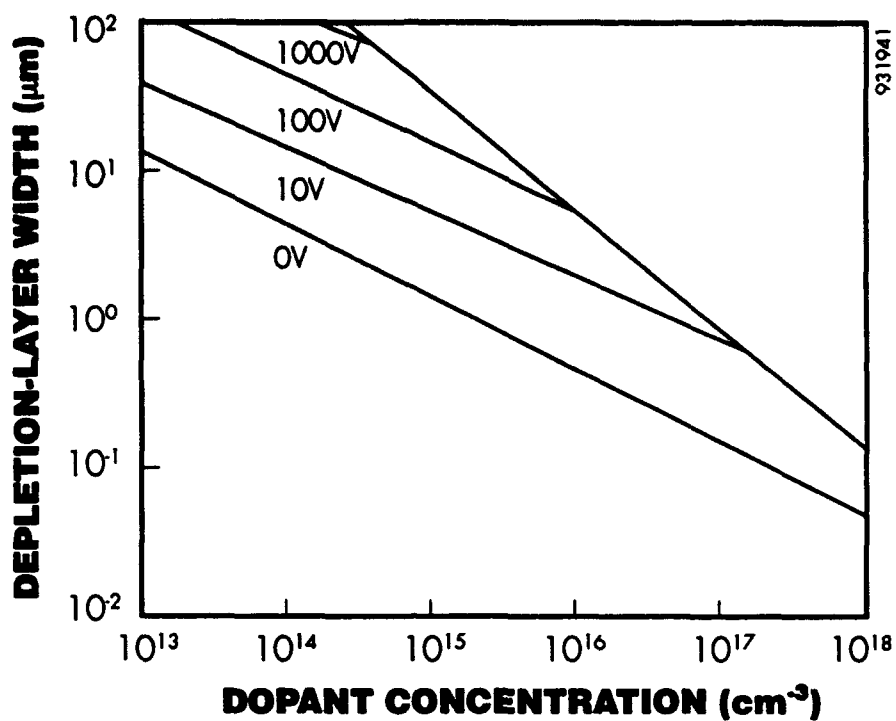


Figure 1 Depletion layer width as a function of reverse bias for GaAs diode.

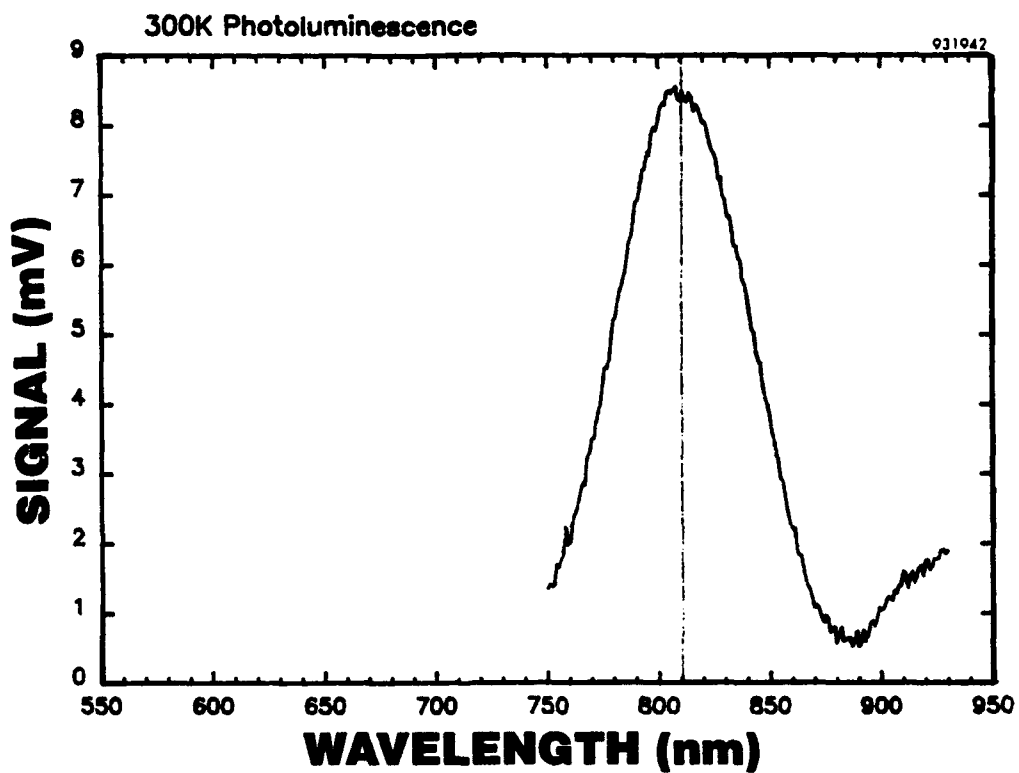


Figure 2 Photoluminescence spectrum of best AlGaAs cladding layer, grown by MOCVD.

2.2 Number of Modes which Will Propagate in a Waveguide

The propagation of guided waves in a waveguide is governed by the relationship,

$$\tan\left[(m + 1)\frac{\pi}{2} - \frac{T}{\lambda}\pi n_g \cos\theta_m\right] = \frac{\cos\theta_m}{(\sin^2\theta_m - \sin^2\theta_c)^{1/2}} \quad (1)$$

where m is the mode number, T is the guide thickness, θ_m is the angle of propagation of the m^{th} mode, and n_g is the refractive index of the waveguide. Here the critical angle is given by,

$$\sin^2\theta_c = \frac{n_c^2}{n_g^2} \quad (2)$$

To cut off the m^{th} mode requires that,

$$\sin\theta_m = \sin\theta_c = \frac{n_c}{n_g} \quad (3)$$

whereupon,

$$(m + 1)\frac{\pi}{2} - \frac{T}{\lambda}\pi n_g \cos\theta_m = \frac{\pi}{2} \quad (4)$$

Simplifying,

$$T_m = \frac{m\lambda}{2n_g(1 - \sin^2\theta_m)^{1/2}} \quad (5)$$

Here T_m is the minimum thickness of the waveguide which will cut off the m^{th} mode. (Notice that because the fundamental mode has $m=0$, therefore it cannot be cut off.)

Using equation (2), this can be expressed as,

$$T_m = \frac{m\lambda}{2(n_g^2 - n_c^2)^{1/2}} \quad (6)$$

For the present program, we must consider the GaAs waveguide with $\text{Al}_x\text{Ga}_{1-x}\text{As}$ cladding. We shall operate at $\lambda = 1059$ microns (the Nd:YAG laser). From Figure 3, we find that at 1059 microns, GaAs has $n_g = 3.49$. Therefore, using Equation (6), we can calculate the number of modes which can be supported in a GaAs waveguide, depending on the aluminum concentration in the cladding.

Our test sample was found to have 7.7% aluminum, as described above. Using Figure 4, we find that at this aluminum concentration, $\Delta n = .04$, and therefore $n_c = 3.45$. Substituting in Equation (6), we arrive at,

$$T_m = m \frac{\lambda}{1.054} \quad (7)$$

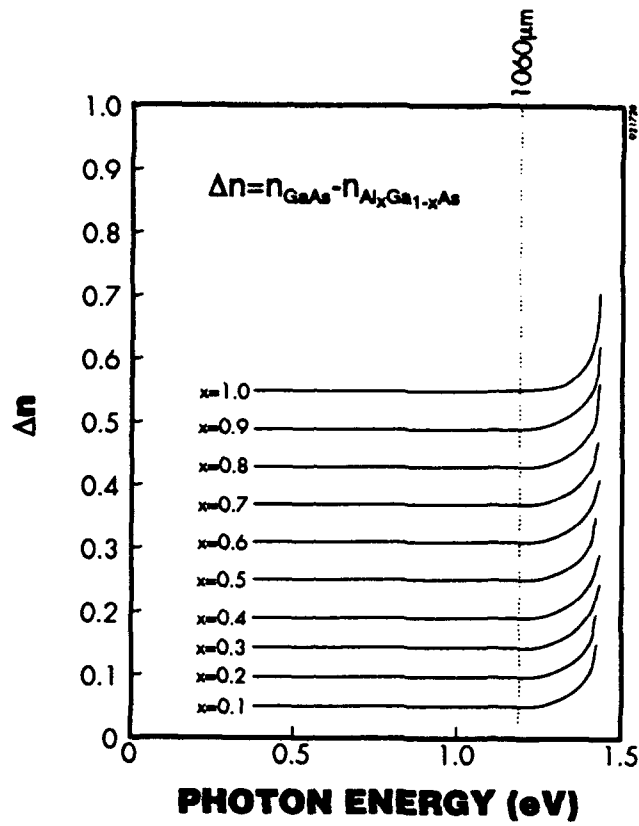


Figure 3 *Refractive index steps between GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ as a function of photon wavelength.*

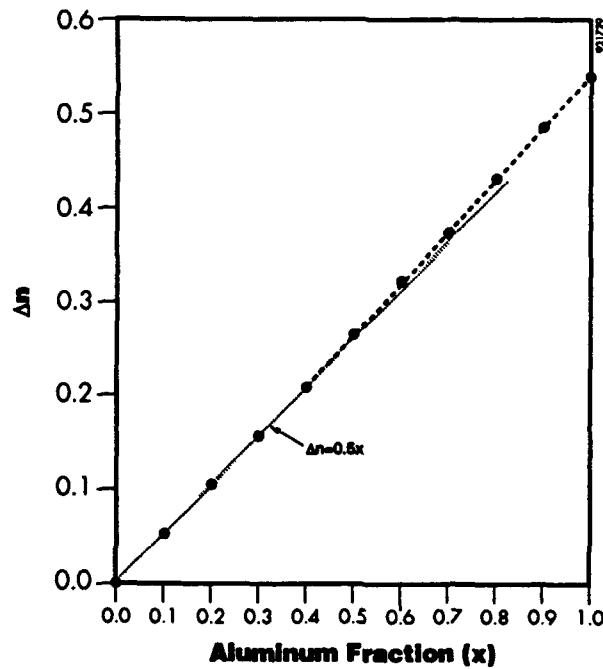


Figure 4 *Refractive index step between GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ at 1059 nm as a function of aluminum content.*

So it's clear that a one micron guide will support only the fundamental mode, a two micron guide will allow the first harmonic to propagate, etc. Thus we should not have a fundamental problem here.

2.3 Laser Entry into Waveguide

It is essential that the laser wavefronts should only be allowed to enter the waveguides, and not be allowed to also propagate through the air above, the cladding, or the substrate. Recall that these are all transparent at 1059 nm. Such stray light would wash out the desired interference pattern in the far field. Therefore, we have designed a grating mask containing arrays of slits. The slits will be mechanically aligned with the waveguides, while the chromium metal that is deposited onto the rest of the glass plate will reflect any other light from the Nd:YAG laser.

The dimensions of each of the gratings are given in Table I. The rows of the table are arranged as increasing number of slits on the mask, while the columns give the ratio of slit width s to the grating period w .

TABLE I

No. of slits	COLUMN								
	1	2	3	4	5	6	7	8	9
2	1.0/1.0	1.25/1.0	1.5/1.0	1.75/1.0	2.0/1.0	2.0/1.25	2.0/1.5	2.0/1.75	2.0/2.0
3	1.0/1.0	1.25/1.0	1.5/1.0	1.75/1.0	2.0/1.0	2.0/1.25	2.0/1.5	2.0/1.75	2.0/2.0
4	1.0/1.0	1.25/1.0	1.5/1.0	1.75/1.0	2.0/1.0	2.0/1.25	2.0/1.5	2.0/1.75	2.0/2.0
5	1.0/1.0	1.25/1.0	1.5/1.0	1.75/1.0	2.0/1.0	2.0/1.25	2.0/1.5	2.0/1.75	2.0/2.0
6	1.0/1.0	1.25/1.0	1.5/1.0	1.75/1.0	2.0/1.0	2.0/1.25	2.0/1.5	2.0/1.75	2.0/2.0
8	1.0/1.0	1.25/1.0	1.5/1.0	1.75/1.0	2.0/1.0	2.0/1.25	2.0/1.5	2.0/1.75	2.0/2.0
10	1.0/1.0	1.25/1.0	1.5/1.0	1.75/1.0	2.0/1.0	2.0/1.25	2.0/1.5	2.0/1.75	2.0/2.0
12	1.0/1.0	1.25/1.0	1.5/1.0	1.75/1.0	2.0/1.0	2.0/1.25	2.0/1.5	2.0/1.75	2.0/2.0

Figure 5 is a sketch of one column of the grating mask, indicating the dimensions involved.

2.4 Multiple Slit Interference

We have simulated the beam steering operation of our GaAs/AlGaAs waveguide phase modulator. The interference pattern from multiple slits is generated according to,

$$I = \frac{1}{N^2} \frac{\sin^2(N\pi \frac{P}{\lambda} \sin \theta)}{\sin^2(\pi \frac{P}{\lambda} \sin \theta)} \quad (8)$$

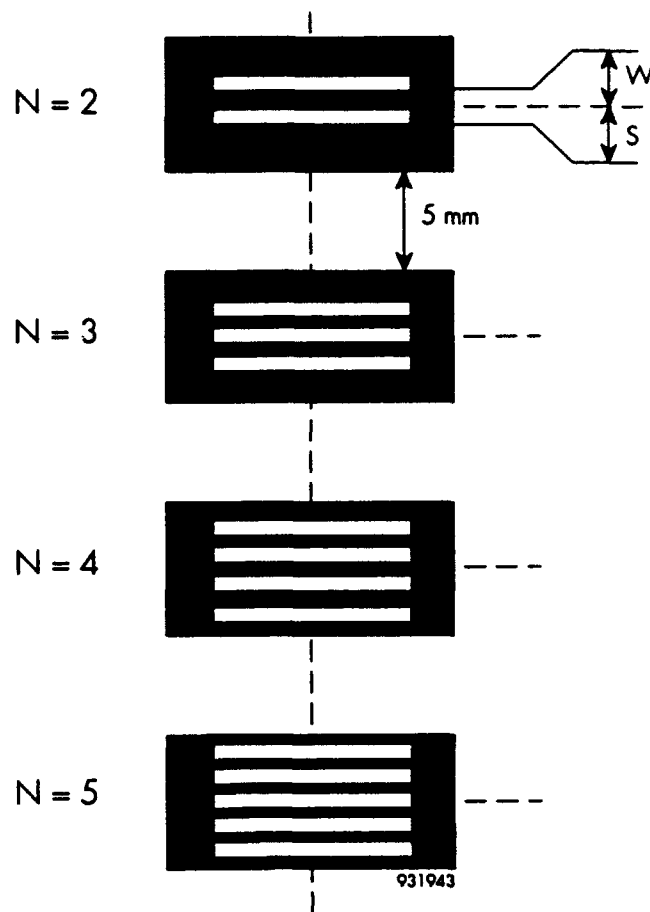


Figure 5 An example of one column of the grating mask.

where θ is the angular deviation from the propagation direction (z-axis) of the incoming laser beam, N is the number of slits, and p is the period of the slits. Because the waveguides are narrow, we also took into account diffraction at each slit, given by,

$$J = \left[\frac{\sin(\pi \frac{w}{\lambda} \sin \theta)}{\pi \frac{w}{\lambda} \sin \theta} \right]^2. \quad (9)$$

The observed pattern will follow the product of these two functions. Figure 6 shows the interference pattern that results when the waveguide width $w = 2$ microns, the period of the guides is 4 microns (that is, the cladding between the guides is 2 microns wide), and the wavelength is 1 micron. There is a fundamental lobe, and two smaller side lobes. Figures 7 and 8 are cross-section views (that is, looking at the waveguides from the side, parallel to the grown layers) which simulate the far field interference patterns, showing what can be expected, with no bias applied to the structure. It can be seen that if the period is equal to the wavelength, as in Figure 7, then only one beam will be present in the output beam. Larger periods (Figure 8) allow higher order spatial modes to be present. It is clear that much optimization of the physical structure will be needed during subsequent phases of this program.

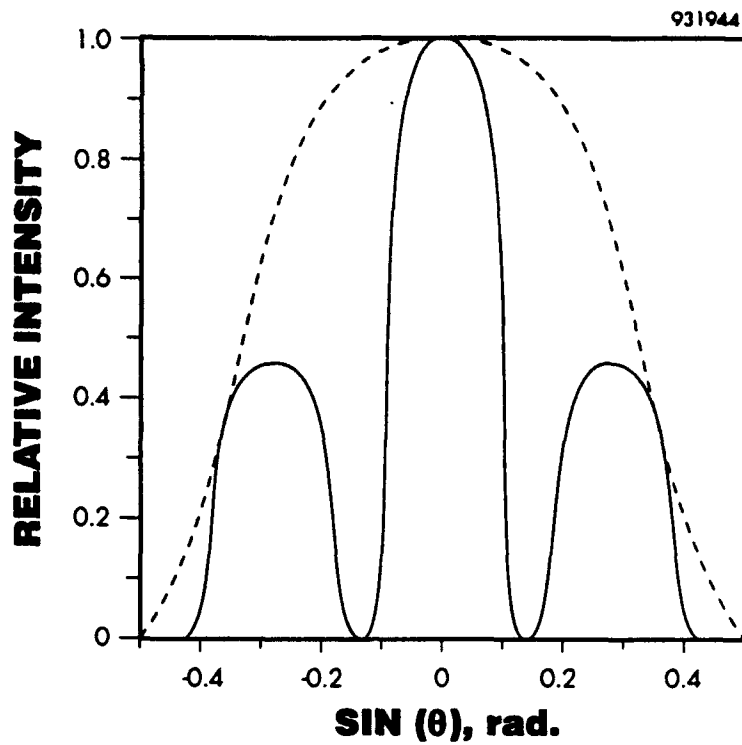


Figure 6 *Far field interference pattern generated by two slits each 2 microns wide, with 4 micron period.*

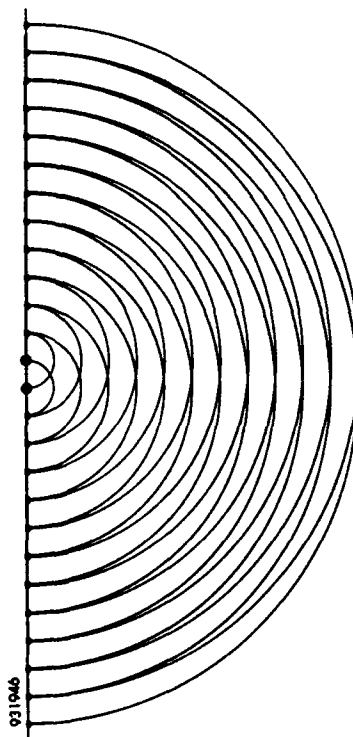


Figure 7 *Interference pattern between two sources separated by one wavelength.*

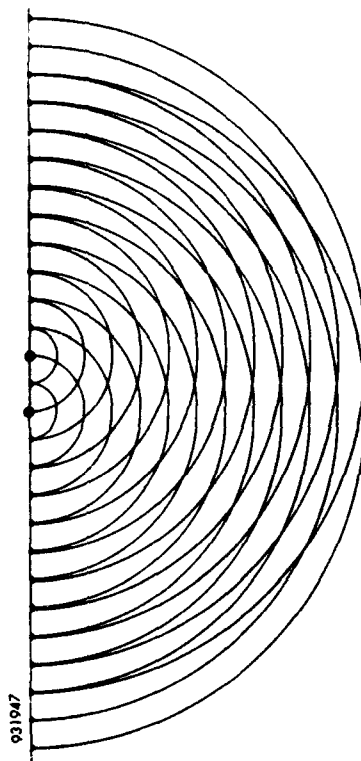


Figure 8 *Interference pattern generated by two sources separated by two wavelengths.*

3 SUMMARY

According to the extensive calculations performed under Task 1 of this program, it does not appear to be possible to demonstrate steering of the Nd:YAG laser using a Si/SiO₂ waveguide, because the required dimensions are far too small to be practical. A much more practical approach has been found with a GaAs/Al_{0.02}Ga_{0.98}As waveguide system, and the structure has been designed. We have determined that the minimum aluminum concentration that can be achieved under calibrated conditions in our reactor is about 8%; to reject all but the fundamental mode, our waveguide will have to be one micron wide. Simulations of waveguide performance have indicated that the thickness of the cladding between the guides should not exceed the wavelength of the light, if higher order harmonics are to be avoided in the far field pattern. We are presently growing the diode structures and evaluating their characteristics.

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