MANIPULATION OF LIGHT WITH MAGNETO-OPTIC STRIPE DOMAIN FILMS

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ABSTRACT

Magnetic diffraction grating materials are currently being developed to provide a simple means of deflecting light in a two-dimensional, solid-state fashion. The most promising material, for several applications, appears to be bismuth substituted iron garnet films in epitaxial form. Calculations indicate that deflection efficiency greater than 60% is possible in the near-infrared region of the spectrum. Within the field of view of the deflector, measurements predict that 10^5 resolvable spots can be expected. Applications include 1) general purpose deflection of free laser light, 2) image processing of extended sources such as transparencies, 3) programmable lensing, and 4) fiber optic matrix switching.

MAGNETO-OPTIC LIGHT DEFLECTOR

The active component of this deflector is a dynamically alterable, solid-state phase diffraction grating that is the energetically favored domain structure of properly configured magnetic materials. A description of the deflector follows.

Diffraction of a light beam occurs as a result of periodic variations in the wave amplitude or phase across a wave normal surface. Magnetic stripe domain arrays can introduce a periodic 180^o phase variation in an incident optical field, through magnetic birefringence. A stripe domain is a long, straight region of uniform width in which the magnetization is nearly constant. Typically, the width can vary from .5 micron to 30 microns or more while the length can extend to several centimeters.[1] Stripe domains in a given sample may or may not have equal width, depending on sample properties and on imposed magnetic fields.

Consider a linear array of stripe domains in a magnetic platelet as depicted in figure 1. Adjacent stripes have $\hat{z}$ components of magnetization that are antiparallel and usually have a continuous component in the x y plane. Because of the Faraday effect the E_x and E_y components of an incident optical field suffer clockwise rotation in odd-numbered stripes and counterclockwise rotation in even-numbered stripes. This differential rotation provides an electric component that is orthogonal to the incident polarization and has 180^o alternations (parallel and antiparallel to $\hat{y}$) that match the spatial period of the domains. The process operates uniformly for all incident polarizations, including random.

In the far-field emerging light adds constructively at angles θ_n, given by

$$\sin \Theta_n = \frac{n\lambda}{\Lambda} ,$$

where n is the order number, λ the incident wavelength, and Λ the grating period. In the special case where each stripe has the same width, even orders are suppressed. Magnetic apodization at the transitions between even and odd stripes discourages higher orders, as well.

The n^{th} odd-order power diffraction efficiency for a square phase grating is found from

$$\frac{I_n}{I_o} = \frac{4}{n^2\pi^2} e^{-\alpha(\lambda)t} \sin^2 F(\lambda)t ,$$

with α the optical absorption coefficient, t the material thickness, and F the Faraday rotation.[2] Figure 2 shows the potential total efficiency of several candidate crystalline deflector materials in the visible and infrared region of the spectrum, based on reported values for F and α.[3-6]

In order to alter the grating in a solid-state dynamic fashion, reliance is made on the strong coupling of the material magnetization and applied magnetic fields either coplanar with, or perpendicular to, the stripe domains. There are several ways in which a magnetic grating can be field programmed to deflect light. A perpendicular field changes the stripe width, periodicity, or both, causing linear deflection and perhaps a shuffling of light amongst the various allowed orders. If the field is applied in the plane, and collinear with the domains, then the stripe width varies with H^{-1}, increasing the diffraction angle with increases in field intensity. Finally, if the field is applied to a general direction in the plane, the grating is re-established collinear to the field, resulting in azimuthal deflection. For some materials the field strength necessary to cause deflection in the annular field of view is less than that required for Lorentz deflection of electron beams in CRTs. Thus, microsecond switching speeds are possible with watt level electrical power.

GARNET

Of the deflector candidates contrasted in figure 2, rare earth iron garnet is presently the preferred material for a variety of reasons. It is readily obtainable as epitaxial films up to 100 microns thick grown on gadolinium gallium garnet, commonly employed as magnetic bubble memory substrates. Stable stripe domain arrays of sufficient quality to provide 10^5 resolvable spots in the annular field of view have been observed. Curie points to 550°K insure that the magnetization is nearly constant over a wide temperature range, including room ambient. The applied fields required to manipulate the stripe domains are on the order of 100 oe., derivable from computer controlled Helmholtz pairs or strip lines in close proximity to the crystal. With bismuth doping the Faraday rotation can reach $50,000^\circ$/cm in the visible and $12,000^\circ$/cm in the near-infrared.[7] The optical absorption exhibits a local minimum at the .81 micron fiber-optic wavelength and a large window of near-zero absorption at wavelengths greater than 1.2 microns. Calcium doping has been successfully used to reduce the absorption at important wavelengths.[8] From experimental data obtained with a Faraday hysteresigraph and a spectrophotometer on thin epitaxial samples it is possible to calculate the maximum deflection efficiency of thick samples or of thin samples operated inside an optical resonant cavity. The calculation has been done and the results are shown in figure 3. Work is currently under way to experimentally evaluate these expectations and to develop the necessary crystal growth facilities to exploit the potential of bismuth garnet for light deflector applications.

APPLICATIONS

Agile light deflectors based on magneto-optics offer unique solutions to a number of optical switching and processing problems. Obvious applications include laser radar at 1.06 microns and 10.6 microns, focal plane array scanners, and optical communications between moving platforms. Because stripe domain arrays can be plastically deformed by spatially varying fields, adaptive optic processing of images of extended objects can also be performed. In guided wave communications, bismuth garnet, in its present form, serves quite well as a high fanout fiber optic switch.

Adaptive Optics

In a stripe domain grating the periodicity, stripe width, and orientation need not be constants over the aperture. Spatially varying magnetic fields can be utilized to locally modify the deflection of incident light from pointlike sources or from extended sources such as collimated beams or transparencies. By properly tailoring the grating, dynamically alterable compressors or expanders and image rotators can be generated.

One-dimensional compressors or expanders are constructed from the domain pattern that has the basic spatial modulation seen in figure 4a. Both the stripe density and grating orientation are functions of local field. This would be useful for correcting image distortions.

Gratings obtained by converting the linear array of a film with some in plane magnetic component, into the radial array of figure 4b, provide a means for continuous distortionless image rotation if the grating has the appropriate radial stripe density gradient. A geometric optic analysis reveals that the gradient is such that the stripe density is inversely proportional to radius. Then the impressed image rotation angle, B, is found to be

$$B = \tan^{-1} \frac{s\lambda}{2c} \quad ,$$

with s the distance to the post grating image plane and c a quantity that depends on field magnitude and stripe widths. In addition, the image experiences a magnification of sec B. Continuous rotation occurs with intensity changes in the field.

In order to initialize the grating to a radial mode it is necessary to bring a point pole into approximate contact with the film surface. The symmetry in the pole's field causes the grating to assume the desired form but with constant stripe density.

In practice the pole can be supplied by a polished ferrite needle. The inplane field that develops the proper stripe density was found to match the tangential field produced by an extended magnetic polepiece. Thus, it has been possible to observe both the rotation and the scaling properties of the radial domain image processor. Rotations to near 90° were recorded. Since the required polepiece is available in ferrite form, high speed rotation is expected.

Arrays formed from domains that are concentric annuli about a fixed center may act like a Fresnel zone plate; i.e., collimated light focuses on the zone axis when the domain widths satisfy the pertinent Fresnel relations. If the incident light impinges on just a sector of this array as in figure 4c, focusing occurs off the optic axis. In either case, dynamic control of the domains implies dynamic lensing. Most likely, garnet materials for this application are of the bubble type because they have only a perpendicular magnetization component.

Fiber Optic Switch

Useful deflection efficiency at the present fiber optic wavelengths, along with magnetic control of the intrinsic grating in garnet films is the basis for a multiport fiber optic switchboard as seen in figure 5. Information-bearing light, propagating in any or all of the elements of the input fiber 2-dimensional matrix is collimated by gradient index lenses (GRIN). Light from a given fiber lens falls on just one deflector element which steers it to one fiber in the focal plane of the output lens. The switchboard has high fanout with just a single level of optical switching. Greater than 100 X 100 input or output arrays can be accommodated.

Figure 6 shows a basic version of a fiber optic switch that utilizes only the inner circumference of the deflector field of view. Input bus light is tapped by selected output fibers that are arranged at the appropriate positions on the I/O face of a GRIN lens. This version provides a set-and-forget feature; i.e., once the orientation of the stripes has been established by the field coils to direct input light to the selected tap, all coil current can be removed until another tap fiber selection is required.

Meaurements and observations to date indicate that the switch has a number of other desirable features. It is insensitive to incident polarization, making it particularly attractive for fiber optics. Crosstalk can be held to < -20 db. with a fanout of 10. Physical size can be as low as 1 cm^3 as shown in figure 1, a working model of a 1 X 3 switch. Field coil switching is approximately 1 watt with microsecond select time. As a diffraction grating it satisfies the reciprocity theorem and is dispersive, allowing two-way operation of multiwavelength carriers. These attributes provide significant systems potential.

One useful systems device is an optical switch that can access just one output or simultaneously access all outputs, on electrical command. It was demonstrated that the basic stripe domain fiber optic switch can accomplish this because of its adaptive optic capability. With reference to figure 4b, if the stripe grating is switched to the constant periodicity radial format discussed under adaptive optics, the deflection space is a thin annulus at the same deflection angle as for the linear grating. Since the tap fibers are arranged to intercept light at this angle, they are uniformly illuminated with the light propagating in the bus fiber. Thus, all tap fibers are simultaneously selected. This can be implemented by placing a point magnetic pole on the optic axis, just behind the mirror. Switching between single select and the multiselect star coupler mode should occur in microseconds.

Because of its high fanout the garnet fiber optic switch may have use as a residue arithmetic adder for optical computing. Figure 8 is a schematic of a possible modulo 5 adder in which input fiber light represents one addend and the grating selected output represents the other.

SUMMARY

Magnetic stripe domain arrays in bismuth iron garnet epitaxial films are alterable in orientation and grating constant with externally applied magnetic fields generated by high speed deflection circuitry. Optical radiation, incident upon the grating, is thus diffracted in a two-dimensional solid-state fashion. Favorable deflection efficiencies and local control of the grating suggest a number of applications. Further work may lead to compact devices that are applicable to robotics and optical processing.

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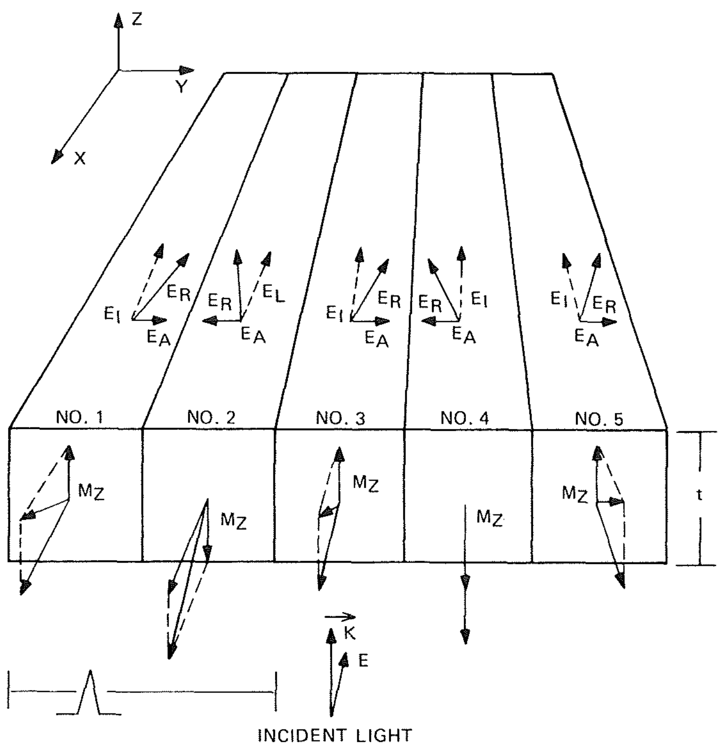

Figure 1.- Magneto-optic diffraction grating.

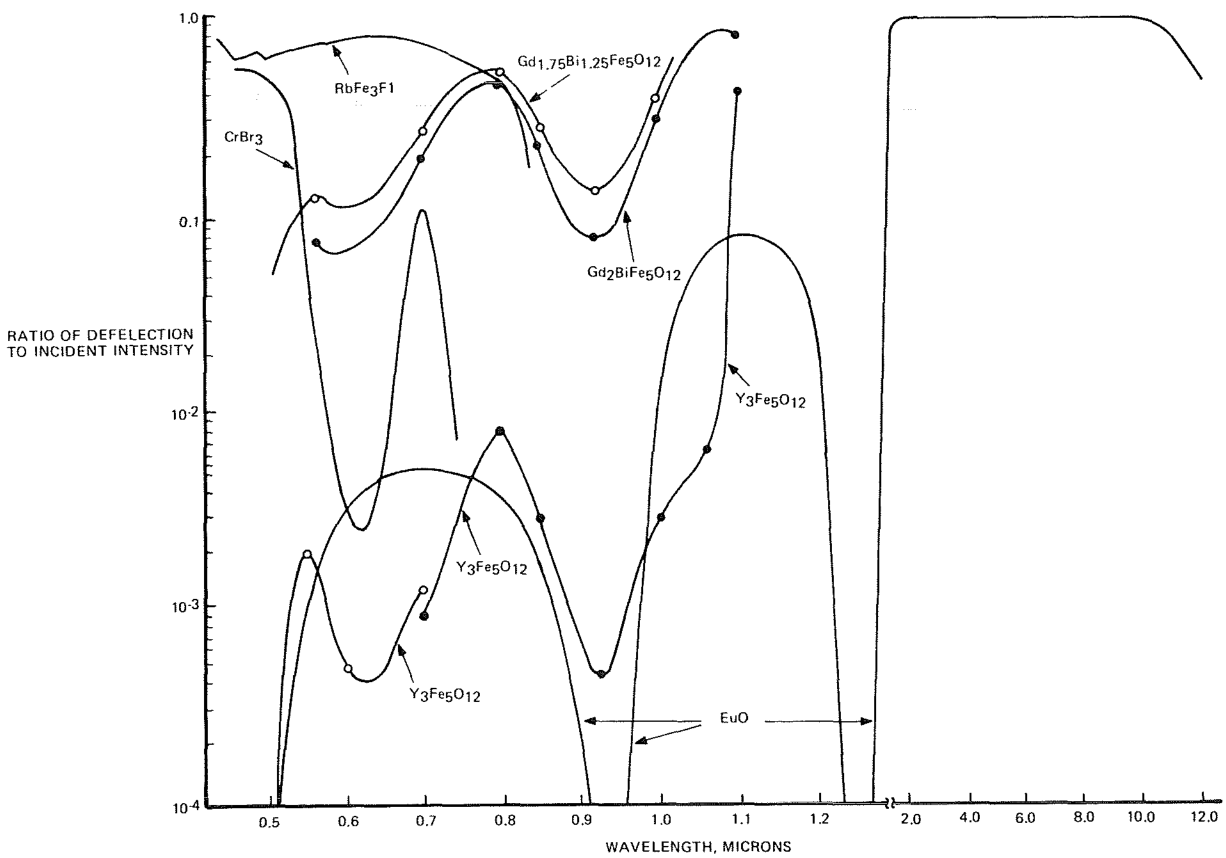

Figure 2.- Calculated diffraction efficiency of stripe domain materials.

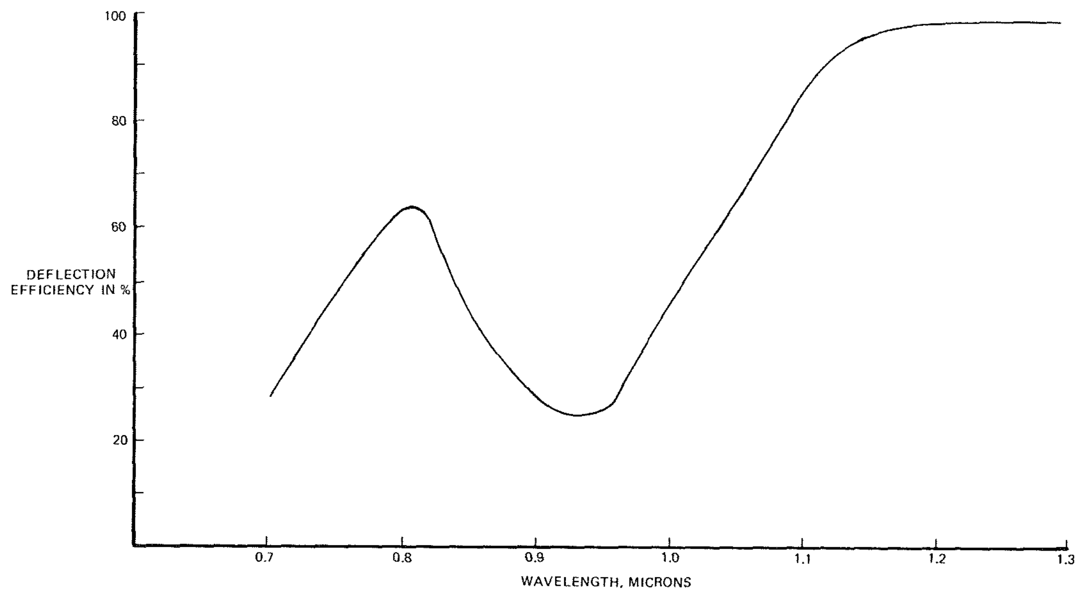

Figure 3.- Calculated diffraction of optimized garnet film.

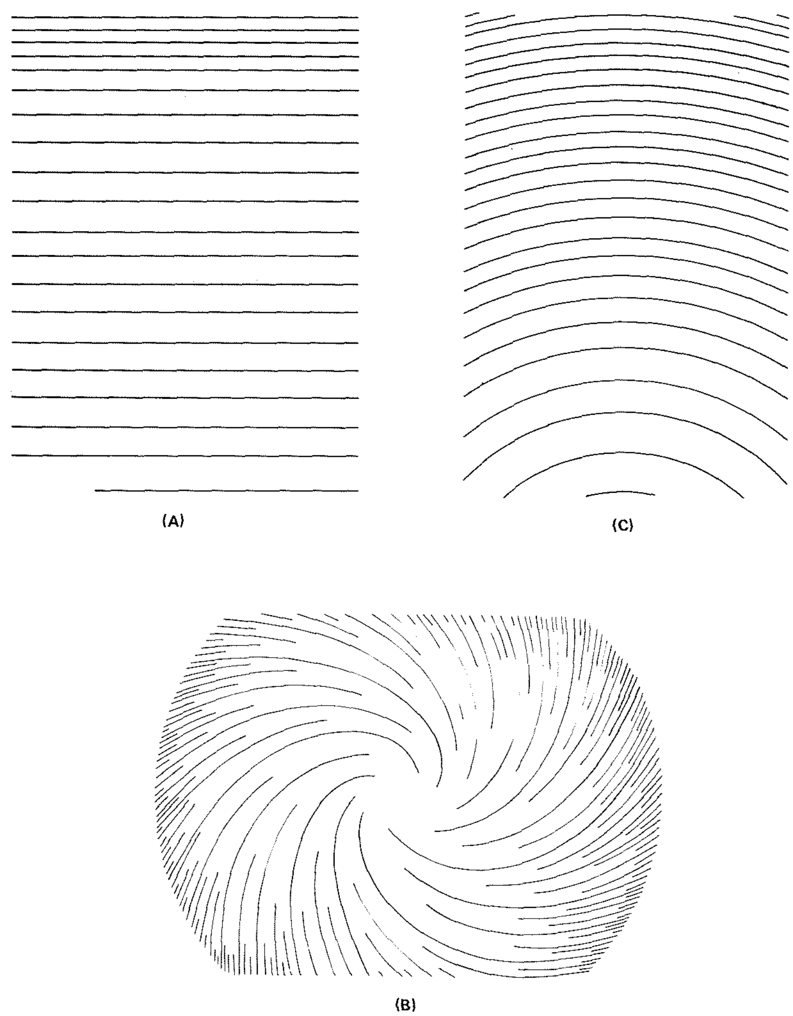

Figure 4.- Adaptive optic configurations. (a) Compression/expansion. (b) Image rotator. (c) Fresnel zone plate.

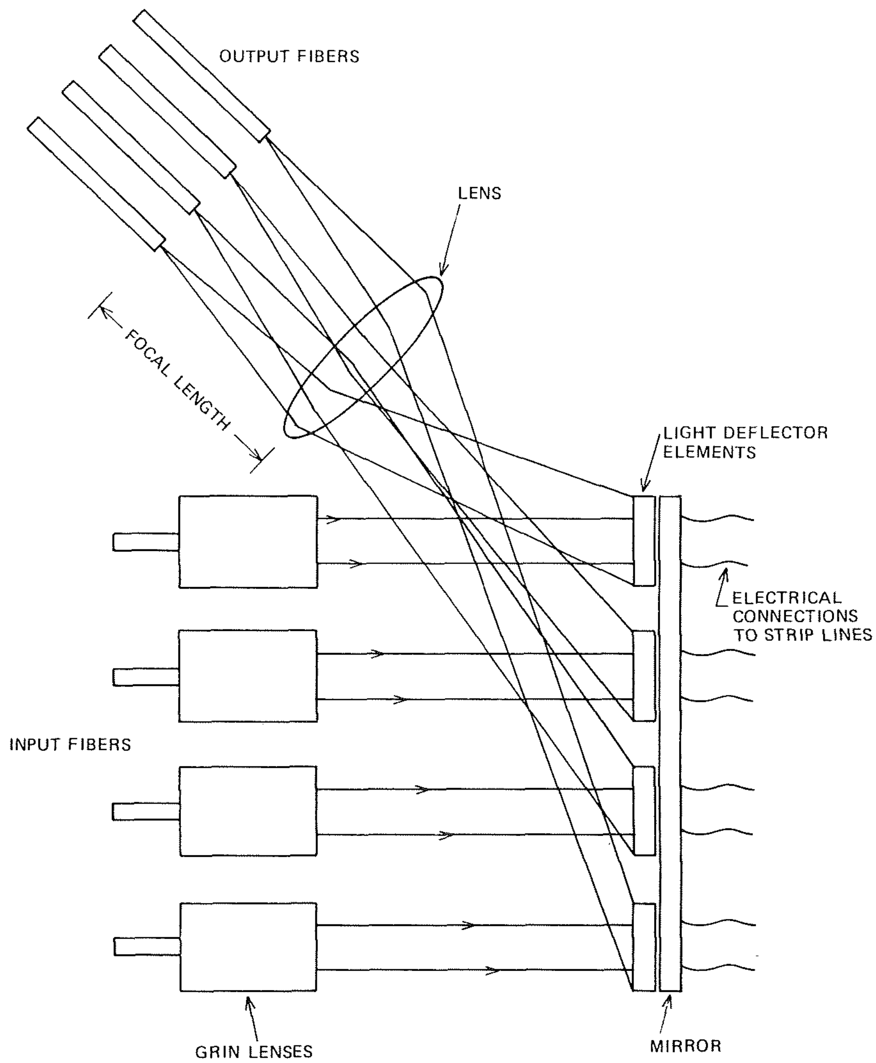

Figure 5.- N X M swithboard.

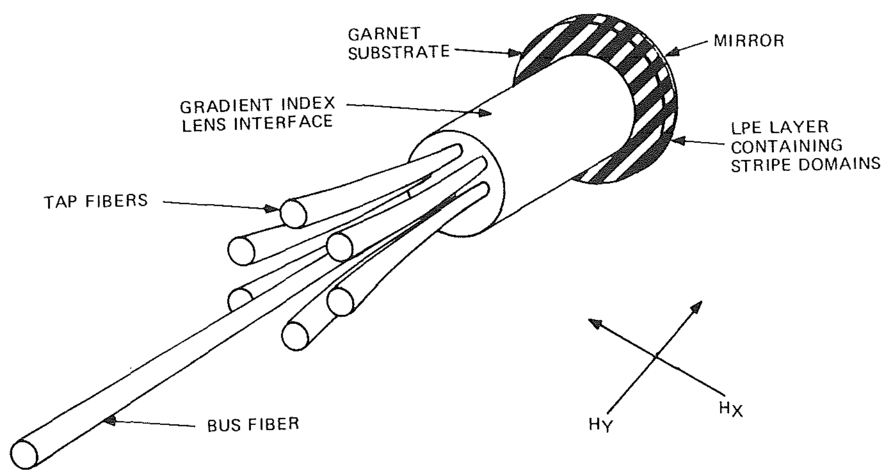

Figure 6.- Fiber optic switch.

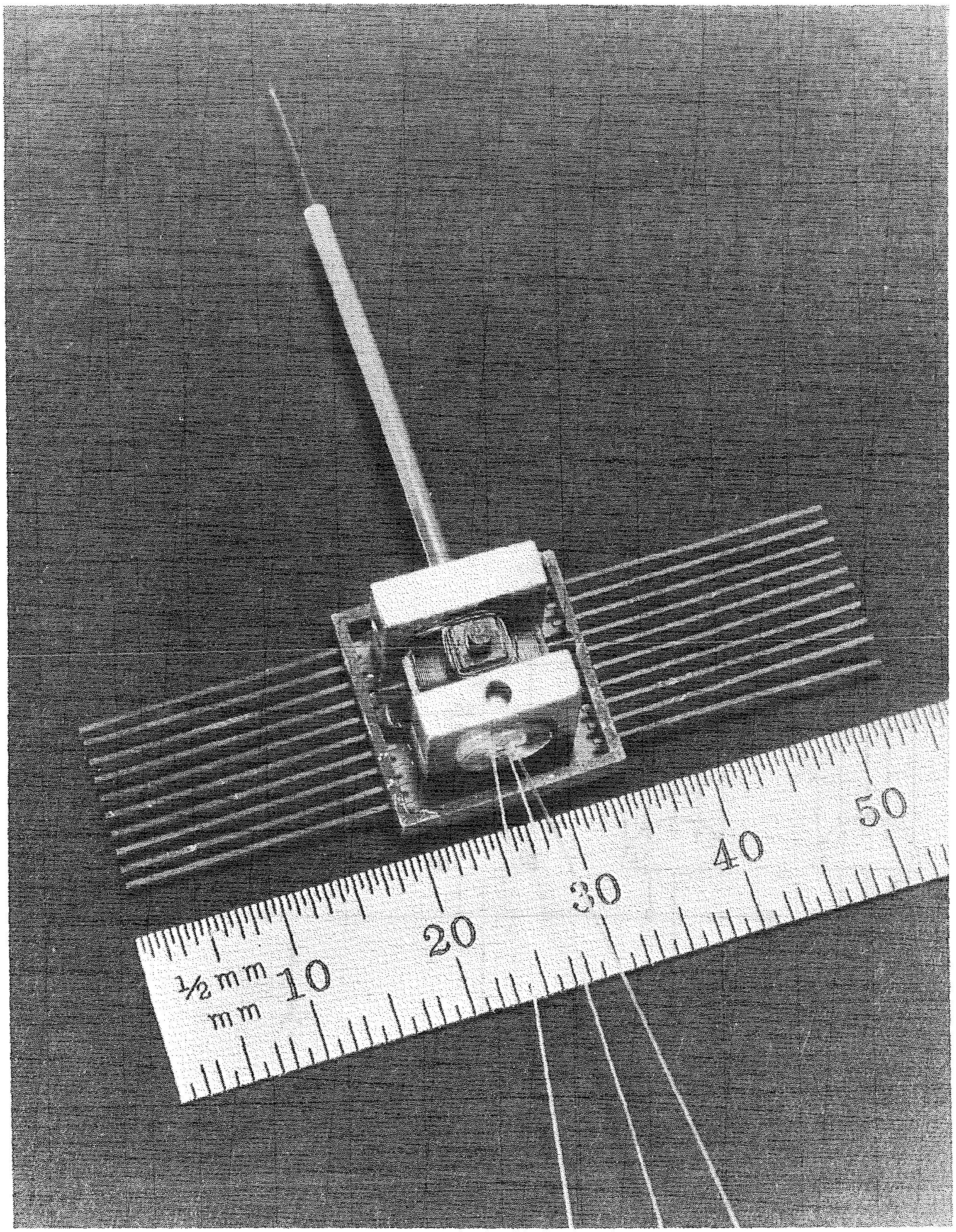

Figure 7.- Operational model of 1 x 3 garnet fiber optic switch.

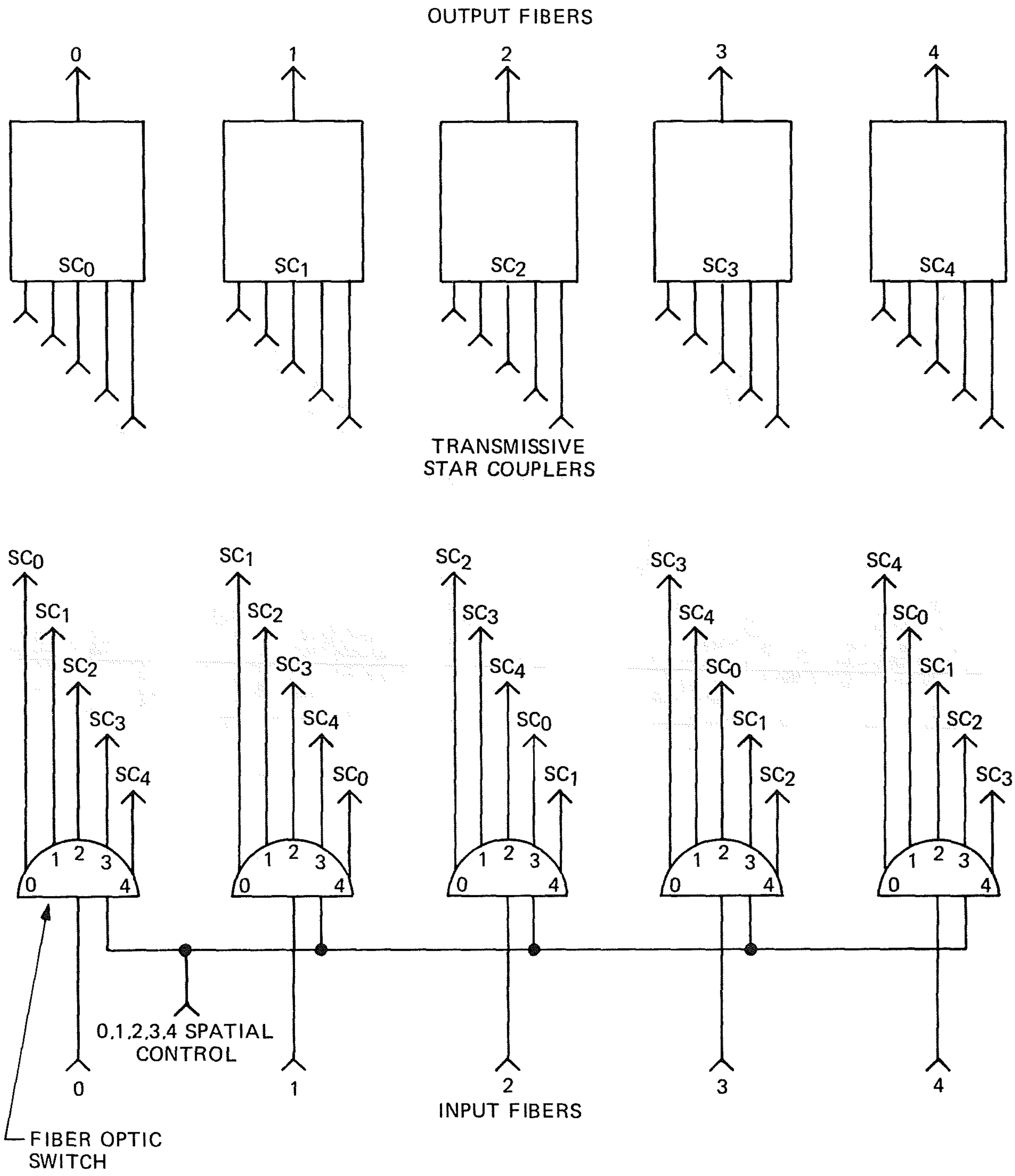

Figure 8.- Residue arithmetic modulo 5 adder.