GUIDED WAVES PROPAGATION AND INTEGRATED OPTICS

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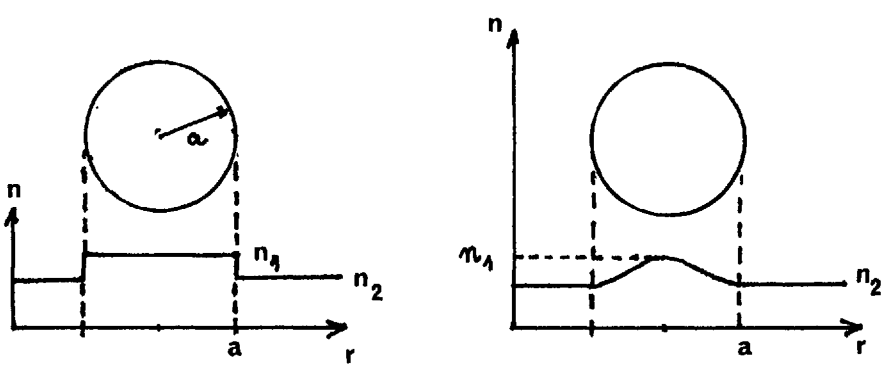
The current art of fiber optics and integrated optics has been reported in several papers and different symposiums. A brief review is presented here in order to describe some principal aspects of the energy light guiding realised by the optical fibers. The area of integrated optics is based on the phenomena involving light guided inside thin films. With the use of semiconductors, it is possible to realise integrated optical circuits. The advantages are the much larger bandwidth and negligible sensibility to interferences of electromagnetic fields of lower frequencies.
The rapid developement of optical communications systems started in 1970, when it was possible to make optical fibers having low attenuation of 20 dB/km. In last years, fibers with attenuation less than 1 dB/km have been realised. Associated with the new suitable sources and detectors, fiber optical transmission systems will find widespread commercial and military applications.

THE TRANSMISSION MEDIUM : PROPAGATION OF THE GUIDED LIGHT

The optical fiber consists of a core of a dialectrical material with refractive index n_1 and a cladding of another material which refractive index n_2 is less than n_1. The optical fiber is represented in figure 1.
The propagation of the guided light inside the fiber can be described by the modal theory. Generally, for the usual optical fibers, the refractive index n_1 of the core is slightly higher than the index of the cladding :

$$n_1 = n_2 (1 + \Delta) \qquad : \qquad \text{with } \Delta << 1$$



step index fiber graded index fiber

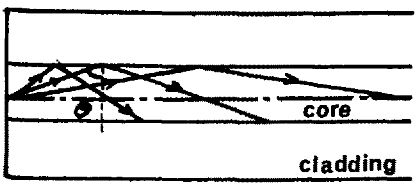
Fig. 1

Another class of optical fibers is concerned by the graded index fibers for which the refraction index varies as a nearly parabolic function as one goes away from the center of the fiber (fig. 1).

$$n_1(r) = n_2(1 + \Delta(r/a)^{\alpha})$$

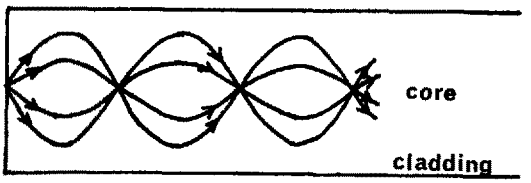
where α has a value close to 2 to maximum fiber bandwidth and is the graded index power coefficient.

For the step index fiber, the propagation of the light in a meridional plane can be sketched in figure 2. The light propagates in the z direction and the physical picture of guided light propagation in then, that of light travelling in zig-zag fashion through the film. In the case of graded index fibers, the beam propagates on a curved way sketched in figure 3. Due to the variation of the refraction index as function of the radial coordinate r, the fiber acts as a continuous lensing medium.



Ray picture in a meridional plane for a top index fiber.

Figure 2



Ray picture for a graded index fiber

Figure 3

Each zig-zag way can be defined with the propagation angle θ. However, all angles θ are not allowed. Only a discret set of angles corresponds to the propagation of the light. These angles are associated to the guided modes. The modal axpressions of the electromagnetic field are obtained from the Maxwell equations. Propagation equation in the cylindrical coordinates is given as:

$$\frac{d^2\psi}{dr^2} + \frac{1}{r}\frac{d\psi}{dr} + \frac{1}{r^2}\frac{d^2\psi}{d\phi^2} + (k^2 - \beta^2)\psi = 0 \qquad (1)$$

r is the radial coordinate, ϕ is the azimuthal coordinate, ψ is the wavefunction of the guided light, k is the wave vector, β is the wave vector component along the fiber axis.

Assuming a wavefunction of the form: $\psi = A\,F(r)\,e^{j\nu\phi}$ (2)

where A is a constant, ν is an integer, equation (1) can be written as :

$$\frac{d^2F}{dr^2} + \frac{1}{r}\frac{dF}{dr} + \left(k^2 - \beta^2 - \nu^2/r^2\right)F(r) = 0 \quad (3)$$

For step index fibers, solutions of equation (3) are given by the Bessel functions and the longitudinal component of theelectric field has the form:

$$E_z = \begin{cases} A\, J_\nu(ur/a)\exp(j\nu\phi) & ; \; r < a \\ B\, H_\nu(wr/a)\exp(j\nu\phi) & ; \; r > a \end{cases}$$

where H is the Hankel function and a is the fiber radius. The boundary conditions require finite solution on axis (r=0) and that the fields disappear at infinity.

$$u^2 = (k_1^2 - \beta^2)a^2 \quad ; \quad k_1 = 2\pi n_1/\lambda_0$$

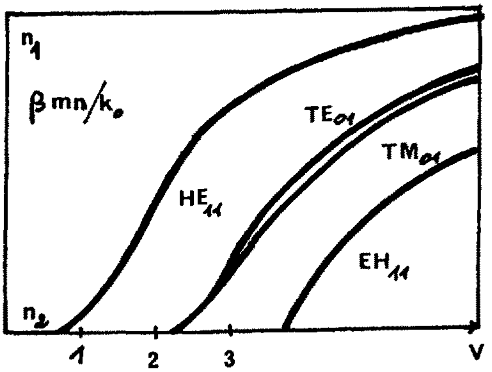
$$w^2 = (\beta^2 - k_2^2)a^2 \quad ; \quad k_2 = 2\pi n_2/\lambda_0$$

λ_o is the wavelength in vacuum.

$$u^2 + w^2 = (2\pi a/\lambda_0)^2 (n_1^2 - n_2^2) = V^2$$

The parameter V is a characteristic of the fiber. The eigensolutions to u and w are determined from the boundary conditions. For $\nu = 0$, the modes are T.E. and T.M. polarized and are radially symmetric. For $\nu \neq 0$, the modes are hybrid and the electromagnetic field possesses six components. The modes are denoted by HE_{mn} or EH_{mn}, depending on whether, the field has a more electric or more magnetic character.
In the case of graded index fibers, the radial field equation can be solved approximately by the Hermite gaussian functions.While the mathematical expressions are more complex, the considerations on the guided modes are the same as those for the step index fibers. The modal description is described in figure 4, which represents the effective modal index β_{mn}/k_o as function of the parameter V for the step index fiber. For V less than 2.405, the fiber has just a single mode denoted by HE_{11}. For high values of V, numerous guided modes can propagate inside the fiber. Single mode propagation is realised with fibers of a few wavelengths in cross sectional dimension and by having small refraction indices differences between the core and the cladding.
The ray theory is useful to define the numerical aperture of the fiber. The numerical aperture is related to the refraction indices of the core and the cladding by the following axpression:

$$\sin\theta = (n_1^2 - n_2^2)^{1/2}$$



Effective modal index β_{mn}/k_o as function of the characteristic modal parameter V.

Figure 4

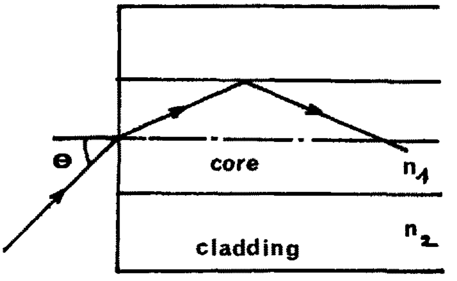


Figure 5

where θ is the incidence angle of the ray on the end of the fiber (figure 5). The numerical aperture, i.e., the maximum acceptance angle is used to calculate the source-fiber coupling efficiencies. When measurements of the numerical aperture are made, the values obtained depend on the length of the fiber. This effect is due to the excitation of the guided modes and leaky modes for short fibers. For long fibers, the power of the leaky modes is lost, after propagating on a long distance. As the higher order modes are lost, the effective numerical aperture decreases, causing the dependance of the numerical aperture on the length. For graded index fibers, the problem is more complex, because the numerical aperture is not a constant across the core as in the case of step index fibers. It is necessary to define a local numerical aperture NA(r) as function of the position r:

$$NA(r) = NA(0)\ (1 - (r/a)^{\alpha})^{1/2}$$

PROPERTIES OF FIBERS

a) Attenuation

The principal fiber characteristic of interest is attenuated due to the intrinsic and extrinsic absorptions of the material which constitutes the fiber. Other contributions of attenuation are brought by inhomogeneities of the index and fiber shape. Impurity absorption arises from metal ions such as iron, copper and cobalt. Another important absorbing ion is OH^-. Figure 6 shows that there is a maximum absorption loss due to the OH^- of fused silica in the 0.9-1 μm region. The attenuation is also due to the scattering of the light. The propagating light can be coupled out of the fiber either by Rayleigh scattering or by guide inhomogeneities such as irregularities of the guide shape or curvature of the guide axis. Attenuation due to scattering is principally attributed to Rayleigh scattering ($\simeq \lambda^{-4}$). The magnitude of the Rayleigh scattering represents the lower limit. Attenuation is yet due to the microbending losses caused by fiber cabling. These losses result from the coupling between guided modes and radiation modes.

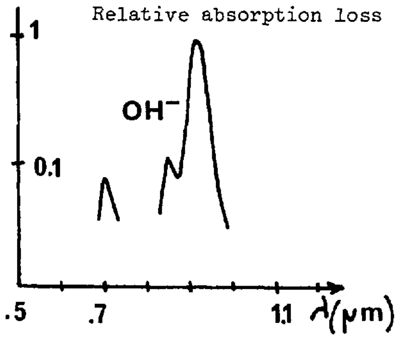


Figure 6

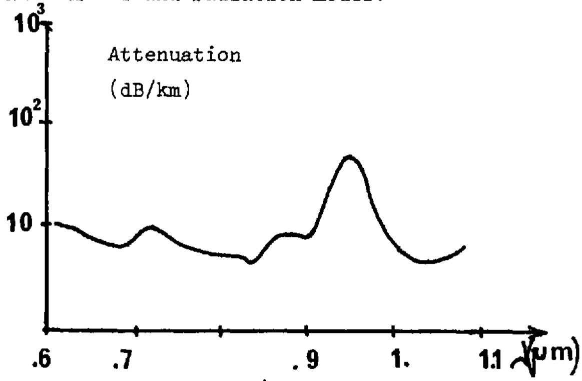


Figure 7

Figure 9 gives the loss of a fused silica multimode fiber versus wavelength. This fiber made by Corning,has a numerical aperture of 0.14 and consists of a doped fused silica core and fused silica cladding whose diameters are 91 and 125 μm respectively. The graph shows that the attenuation is the lowest at 0.85 μm and 1.05 μm, which are precisely the wavelengths chosen for the optical telecommunications.

b) Fiber information capacity

We will comment here the information capacity of the single mode and multimode fibers. The information capacity is considered from the standpoint of digital transmission. The important point is to analyse the different causes which produce the broadening of the pulses when they travel along the transmission fiber. Generally, the spreading is the result of the dispersion characteristic of the fiber.

For single mode fibers, it has been shown that the pulse spreading depends on the spectral width of the source. For multimode fibers, the spreading is due to group velocity differences between all the modes. Generally, there are three causes of dispersion in a fiber:

1)- Waveguide dispersion which produces a delay effect versus wavelength in each propagating mode.

2)- Material dispersion: for the most glasses, the refractive index depends on the wavelength.

3)- Multimode dispersion: at single freqency, the group velocities are different for the various modes.

For multimode fibers, all three effects must be considered.

With broad band sources, material dispersion and multimode dispersion must be considered. With narrow band laser and single mode fiber, the material dispersion is the most important cause. The evaluation of the dispersion characteristics of a fiber is obtained from the specific group delay (second per meter) .
It has been shown by Glodge that the group delay has the following expression, with the assumption that the core-cladding dispersion characteristics are similar:

$$\tau = \frac{1}{c}\left\{N_1 + (N_1 - N_2)\frac{m}{M}\right\}$$

where $N_1 = d(kn_1)/dk$; $N_2 = d(kn_2)/dk$; m is a mode group number and M is its maximum value. The parameters n_1, n_2 are the phase refractive indices of the mode and N_1, N_2 are the group refractive indices of the mode.
They are related to the phase velocity by the following expressions:

$$\frac{\omega}{k} = \frac{c}{n} \qquad \frac{d\omega}{dk} = \frac{c}{N} = \frac{c}{d(k_0 n)/dk_0}$$

From the above expression of τ, it is easy to calculate the multimode group delay distorsion. With $\Delta = 0.01$ and $n_1 = 1.46$, τ is about 50 ns/km.
Material dispersion is particularly significant for single mode fibers. The pulse spreading over a length L is given approximately by:

$$\tau = \frac{L}{c}\,\frac{\Delta\lambda}{\lambda}\,\lambda^2\,\frac{d^2 n_1}{d\lambda^2}$$

where $\Delta\lambda/\lambda$ is the spectral width of the source, $\lambda^2 d^2n_1/d\lambda^2$ is the material dispersion. This spreading appears because the group velocity of the mode is a function of the wavelength. It has been shown for a fused silica single mode that the material dispersion cancels exactly the wavelength dispersion when the wavelength λ equals 1.32 µm. At this wavelength, the bandwidth is very high (more than 100 GHz/km). The used source is an injection laser having a narrow linewidth of about 0.1 Å. The modal dispersion is the strongest cause of the delay spread. The maximum delay spread can be calculated easily from geometrical optics considerations leading to the expression:

$$\tau = \frac{(NA)^2}{2n_1 c} \quad \text{; for step index fibers.}$$

$$\tau = \frac{(NA(o))^4}{8n_1^3\, c} \quad \text{; for graded index fibers.}$$

It appears from the above relations that the dispersion corresponding to the parabolic profile is $\Delta/2$ times smaller than the dispersion of the step index fibers. The width of a pulse propagating in a graded index fiber with the index profile $n(r) = n_1\,(1 - (r/a)^{\alpha})$, has been calculated as a function of the profile shape fector. For fused silica type, the optimum profile is nearly parabolic: $\alpha \simeq 2$.

The optimal value of α can be approximated by $\alpha \simeq 2(1 - 1.2\Delta)$.
Small deviations from the optimal value produce rapidly degradations on the capacity of the fiber. It is difficult to obtain practically the optimal profile.
We must notice the mode coupling effect on the capacity of multimode fibers. During the propagation, higher order power is lost by the coupling effect with the radiation modes. In this case, the numerical aperture is smaller and produces a reduction of the dispersion.
Mode mixing is also an effect which tends to equalize the modal velocities. Modal coupling reduces the spread of velocities and the coupled modes tend to possess a common velocity. Modal mixing is due to the fiber material inhomogeneities, diameter fluctuations and refractive index variations.

INTEGRATED OPTICS

We give now a brief tutorial introduction and a review of the growing research field of "Integrated Optics". We have given above the different properties of multimode fibers because fiber systems, under study today use multimode fibers in which a thousand modes can propagate. On the contrary, integrated optical circuits and devices are single mode structures. Single mode fibers are just needed for higher transmission speeds and longer transmission distances.
Integrated optics covers all the guided wave techniques used to realise new optical devices and waveguides. The waveguide allows to confine the light energy to a very small cross section, over long distances. The purpose of integrated optics is to construct optical guided wave devices with a very good thermal and mechanical stability. It is allowed to think that one will be able to realise on the same substrate, different integrated devices like integrated sources, integrated modulators in analogy with integrated circuits in electronics.
The planar waveguides used in integrated optics are dielectric waveguides which can be represented by a thin film of higher refractive index than the surrounding medium. They act like filters, wavelength multiplexes, directional couplers or detectors. The planar waveguide confines the light in one dimension.

- Dielectric waveguide.

The dielectric waveguide is shown in figure 8 and 9 where n_f, n_s, and the refractive indices of the film, substrate and cover materials. For the propagation of a guided wave, it is necessary to choose:

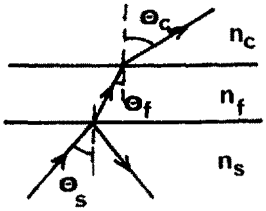
$$n_f > n_s, nc$$

The light is guided inside the film if the energy is confined in the guide or near both interfaces. The guide supports radiation modes when the light is spread outside the film.

If the propagation angle θ is greater than the critical angle θ_ℓ

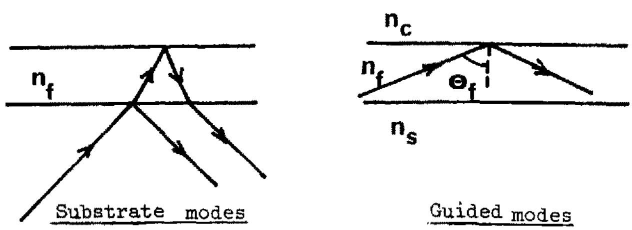
$$\sin \theta_\ell = n_s/n_f$$

the wave undergoes total reflection on the upper and lower interface. In this case, the modes are guided. Figures 8 and 9 represent the different types of modes.



Radiation modes

Figure 8

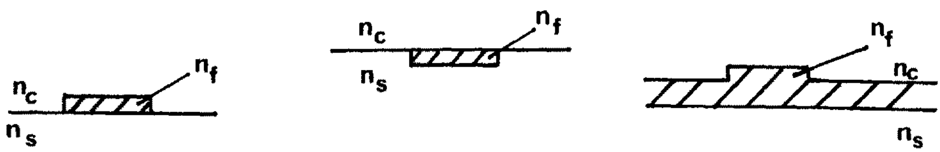


Substrate modes

Guided modes

Figure 9

Strip guides confine the light in two dimensions. The refractive index n_f is always larger than the surrounding. Different strip guides are described in figure 10.



Raised guide

Embedded guide

Ridge guide

Figure 10

Strip guides are used to form various circuit patterns. If two identical strip waveguides are parallel and close to each other over a length L, they will couple energy due to the evanescent field between them. In this case, all the energy can be transferred from one waveguide to another if the coupling length satisfies the relation: $\kappa L = (2m + 1)\ \ /2$; $m = 0,1,2,\ldots$ This principle is the basis of the directional coupler described in figure 11.

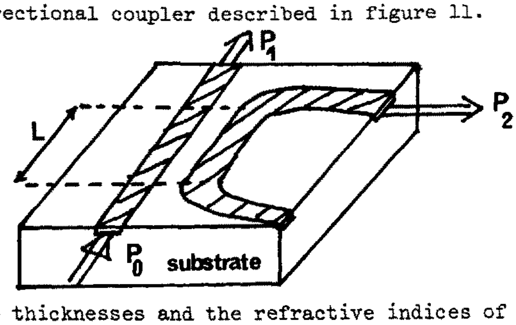


Figure 11

Directional coupler made of strip guides.

The incident energy P_o in guide 1 can theoretically be transferred to guide 2.

The thicknesses and the refractive indices of the strip guides depend on the method of fabrication. Typically, most guides have index differences with the substrate of the order of 10^{-3}. The thicknesses are of the order of a few microns.

The physical picture of the guided light propagation is that of light travelling in zig-zag path. The electromagnetic field is the superposition of two plane waves which are totally reflected on the interfaces limiting the guide. For a guided wave, the propagation is allowed only for a discret set of angles θ_f. This propagation is described by the well known transverse resonance condition:

$$2k\, n_f\, d \cos \theta_f - \psi_s - \psi_e = 2m\pi$$

where $k = \omega/c$; ω is the angular frequency: c is the light velocity; θ_f is the propagation angle of the mode; ψ_s and ψ_c are the phase shifts imposed on the reflected waves; m is an integer (0,1,2, ...) which defines the mode number; d is the guide thickness (Figure 12).

The guided wave propagates in the z direction with the propagation constant

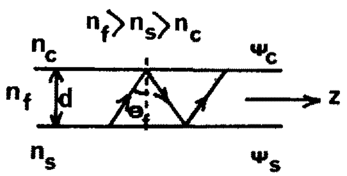


Figure 12

$$\beta = k\, n_f \sin (\theta_f)$$

It is often convenient to use the effective guide index defined by:

$$N_f = \beta/k = n_f \sin \theta_f$$

with $n_s < N < n_f$

The transverse resonance condition is also the dispersion relation giving the propagation constant β as function of the frequency ω and guide thickness d. From this condition, one can obtain the typical ω - β diagram of a dielectric waveguide (figure 13).

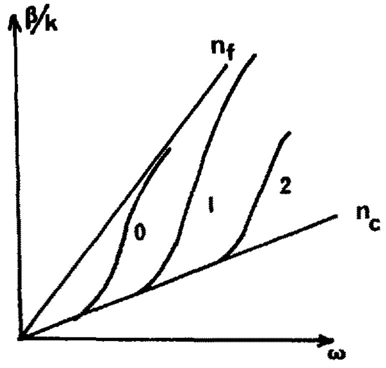


Figure 13

When ω or d increse, β/k tends to the upper bound b_f and more and more modes are guided. On the contrary, when ω (or d) decrease, β/k tends to the lower limit n_s and for small values of the frequency ω or the thickness d, only the first mode (order 0) propagates.

It is convenient to define a normalized frequency and a guide thickness V by:

$$V = k\, d(n_f^2 - n_s^2)^{1/2}$$

a normalized guide index

$$b = (N^2 - n_s^2)/(n_f^2 - n_s^f)$$

a parameter od asymetry of the waveguide

$$a = (n_s^2 - n_c^2)/(n_f^2 - n_s^2); \text{ for T.E.modes}$$

With the above defined parameters, the dispersion relation can be written in the form:

$$V(1 - b)^{1/2}, - \tan^{-1} \sqrt{b/(1-b)} + \tan^{-1} \sqrt{(b+a)/(1-b)} = m\pi.$$

This last relation allows to obtain the dependence of the guide index b as a function of the normalized thickness V for different values of the asymmetry parameter a. By setting b = 0, one determines the cutoff frequencies of the propagation modes.

- Switches and modulators

We have described above the characteristics of the light propagation in a passive dielectric waveguide. These waveguides serve the function of transporting light energy in the same way that conduits carry currents in integrated electronics circuits. In addition to the above passive dielectric waveguides, it is necessary to make active components like switches, modulators and integrated laser sources, such as transistors in integrated electronics. To obtain the light modulation, the electro-optic effect was applied to achieve modulation in a GaAs epitoxial film on a more heavily doped GaAs substrate. Considerable progress was made recently in the technology of guided wave modulators and switches.

The modulator or switch, based on the electro-optic effect, is shown schematically in figure 14. Two single mode strip guides are deposited on a common substrate. These guides are made with an electro-optic material. The two guides are parallel and separated by a gap g for a length L. Outside this **length, the guides separate.** An electric field is applied on the electrodes as shown in the figure. These electrodes are split in the middle to permit the application of voltages of reversed polarities. Without voltage, we have the configuration of the directional coupler. In this case, all the energy in one guide can be coupled to the other guide, if the length L satisfies the relation: $\kappa L = (2m+1)\pi/2$, where κ is the coupling constant between the two guides. With identical guides, the transfer is maximum if the propagation constants are equal: $\beta_1 = \beta_2$

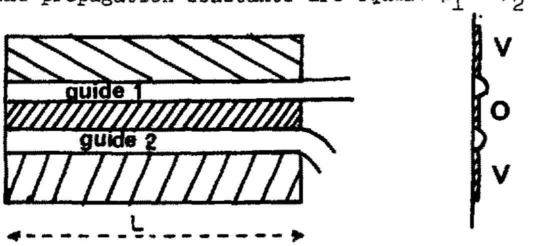


Figure 14

Electro-optic modulator

The light flowing in guide 1 will couple into guide 2 and vice versa.
If the propagation constants are not matched: $\beta_1 \neq \beta_2$, all the light will not be coupled and the coupling length l will be shortened. The modulation of the light can be explained from these considerations. Without applied eletcric field, $\beta_1 = \beta_2$, and the light in guide 1 is totally coupled in guide 2. If a voltage is applied on the electrodes, the effective index of guide 1 will change in the opposite direction from that of guide 2. In this case, β_1 will be different from β_2 and the light will not be coupled in guide 2 and will propagate in both guides. The reader will find in numerous publications the detailed calculations

of the electro-optic modulator performances. We report here the results concerning a modulator made with $LiNbO_3$. With a gap of 2 μm and a coupling length of 1.4 mm, the energy transfer is maximum when V = 2 volts. An approximate calculation shows that the specific energy is 18×10^{-6} W/MHz. As can be seen, high transfer is possible with low voltage and power.

We may note at ounce that switches and optical modulators have to be important components of any optical communication or data transmission system.

By connecting several such switches, one can build networks such as by applications of proper voltages, the light entering in one of the input guides can be switched in one of the output guides. Figure 15 shows an experimental 4x4 switching network.

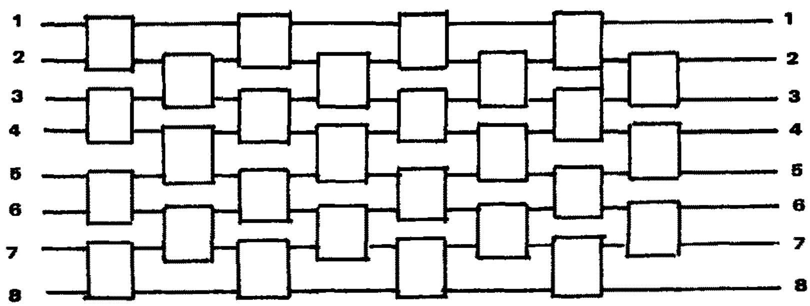


Figure 15

- Filters

The realisation of filters is used for application such as wavelength multiplexing of different channels. Grating structures have been used as filters. A corrugation is made into the surface of a film. The grating has a very short period Λ. It has been shown that a filter has a bandwidth of approximately

$$\Delta\lambda/\lambda \simeq \Lambda/L$$

where L is the length of the periodic structure. The bandwidth is centered at the wavelength λ_o with: $\lambda_o = 2N\Lambda$.

N is the effective index of the guided mode.

CONCLUSIONS

The ramarkable progress made up to date in developing components for use in optical fiber systems has led to a new guided light technology. Propagation loss in optical fibers has been reduced several orders of magnitude. Multimode graded fibers are now produced with low loss characteristics (few dB/km). Injection lasers and LED lifetimes have been improved by several orders of magnitude. Reliability of 10^5 hours is necessary for most practical applications and extrapolated lifetimes in this range have been demonstrated. The age of telecommunications appears to be a reality. The demand for communications has grown considerably over the past decade and continues to increase. One can conclude that optical fibers will have a significant impact on future data transfer applications.

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