Articles

Optical Guided-Wave Devices

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Optical fiber is rapidly becoming the transmission medium of choice for new telecommunication systems. For a true lightwave network to evolve, however, optical control devices such as optical switches and multiplexer-demultiplexers will be essential. Optical guided-wave devices built with photolithographic fabrication techniques and electro-optic substrates are compact, low drive power devices that provide these functions. Research is particularly advanced on integrated-optic devices based on waveguides formed by titanium diffused into lithium niobate. Switch arrays, tunable filters, and high-speed modulators have been demonstrated and used in research systems experiments.

SINCE THE DEMONSTRATION OF THE LASER 25 YEARS AGO, the promise of very high capacity communications through an optical carrier has stimulated widespread research on electro-optical control devices. The promise of broadband optical communications became a virtual reality with the achievement of low-loss silica fiber, whose transmission loss is now as low as 0.16. Light (actually infrared radiation) will play an important role in communications and perhaps in information processing as well. To build sophisticated and flexible optical communication systems, components to manipulate light such as optical switches, modulators, wavelength filters, and polarization manipulators will be required. To provide such compact, high-speed, low drive power, mass-producible optical components for both communications and signal-processing applications is the goal of a field of research referred to as integrated or guided-wave optics (*1*).

Integrated-optic devices are made according to photolithographic and microfabrication techniques. This makes possible mass production in the same way as for electrical integrated circuits. To provide fast and efficient electrical control over light, these devices are made in an electro-optic material—one in which the refractive index of the material can be changed by an applied voltage. Light can be coupled into and out of the devices by attaching an aligned fiber.

The most common electro-optic substrate materials for integrated-optic devices are the semiconductors gallium arsenide (GaAs) and indium phosphide (InP) and lithium niobate, a ferroelectric insulating crystal. Research on lithium niobate integrated-optic devices is currently the most advanced for several reasons. First, high-quality lithium niobate substrates are commercially available in lengths as long as 8 cm. Lithium niobate is a strong, easily polished nonhydroscopic crystal. Most importantly, it has a good electro-optic coefficient, which translates to low control voltages. It also has low optical transmission loss, which is especially important because, for many applications, integrated-optic devices will be useful only if a large (>50%) fraction of the incident light is transmitted through the device. For example, by increasing the throughput of a terminal device, such as a modulator, from 50 to 63% (a 1-dB increase), the transmission distance for a fiber with loss of 0.16 dB/km can be increased by over 6 km. Although there has recently been significant reduction in the losses of waveguides made in GaAs substrates, the high losses in the past have hindered progress in integrated optics in these semiconductor materials. However, unlike lithium niobate, GaAs and InP substrates can be used to make lasers, detectors, and transistors. These substrates offer the exciting potential of monolithically integrated optical and electronic circuits.

Waveguide Fabrication

A dielectric waveguide, on which integrated-optic devices are based, is created by forming a region of higher refractive index surrounded laterally by a region of lower index. Confinement of light in the waveguide channel can be understood as a result of total internal reflection at the channel boundaries. In lithium niobate waveguides, this refractive index increase is conveniently formed by diffusion of the metal titanium into the crystal. The steps to form a strip or channel waveguide, which can be butted directly to a circular fiber, are shown in Fig. 1 (*2*). The processing is similar to that used for electrical integrated circuits. Photoresist is a light-sensitive material spun onto a polished, clean lithium niobate substrate. A mask with the desired waveguide pattern is placed in contact with the crystal, which is then exposed to ultraviolet light. After development a channel is left in the photoresist. Titanium metal is deposited, typically by evaporation, over the entire crystal. After the crystal has been placed in a photoresist solvent, the photoresist is removed, taking with it the undesired titanium outside the channel region. What remains is the desired titanium metal strip. The crystal is then heated in a diffusion furnace to a temperature of 1000° to 1050°C for 4 to 10 hours.

The titanium diffuses into the crystal as an oxide and raises the refractive index approximately linearly with the titanium concentration. The diffusion profile is approximately exponential, with a diffusion depth that depends on the diffusion coefficient of the material, the diffusion time, and the diffusion temperature. For guided-wave devices that operate in the wavelength region of 1.3 to 1.55 μm—which is the wavelength region for which silica fiber has its lowest dispersion (pulse spreading) and loss, respectively—typical metal strip widths are 6 to 10 μm, metal thickness is ~0.1 μm, and diffusion depth is ~5 μm. For fixed diffusion time and temperature, the refractive index increase in the waveguide region can be raised by increasing the titanium metal thickness, provided the diffusion conditions are such as to completely diffuse the metal into the crystal. Therefore, the waveguide width and depth and the refractive index difference between the waveguide and substrate, the three parameters that control the waveguide properties, can be

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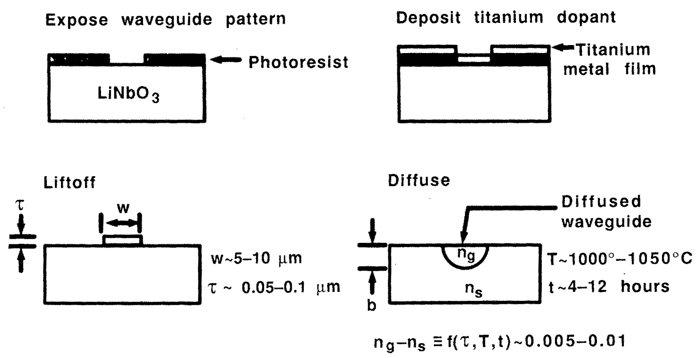

Fig. 1. Fabrication steps to form channel waveguides by titanium diffusion into lithium niobate.

separately controlled in fabrication. Waveguides properly fabricated by this process exhibit propagation losses as low as 0.2 dB/cm at wavelengths of 1.3 to 1.55 μm (*3*).

Optical dielectric waveguides, both planar and fiber, can support (guide) many modes depending on the waveguide-substrate index difference and waveguide dimensions. Each mode has its own transverse amplitude mode profile and effective velocity along the waveguide. A single-mode waveguide, in which the optical intensity profile across the waveguide has a single maximum with an approximately exponential falloff outside the waveguide, can be made by using a relatively narrow and shallow channel ($\sim$10 μm). For several reasons, only single-mode waveguides can be used to make efficient electro-optically controlled guided-wave devices. Early lightwave systems used the larger and more conveniently handled multimode fiber, but single-mode fiber, which can transmit data at much higher rates (theoretically nearly 1000 times as high), is becoming increasingly more popular. In multimode fiber, the mode-dependent velocity causes a variable time delay and spreading of the digital pulses that carry information. The single propagation velocity of single-mode fiber allows it to carry data at higher information rates over longer distances without overlapping neighboring pulses. The rapid increase in popularity of single-mode fiber, with which integrated-optic devices are compatible, has greatly increased the interest and likely applicability of guided-wave devices.

In lightwave systems, the ability to transfer light efficiently between titanium-diffused waveguides and single-mode fibers is essential. To couple light between a dielectric waveguide and a fiber butted against it, the optical modes of the two structures have to be made as similar as possible. This matching might seem to be difficult because fiber is circularly symmetrical, whereas the waveguide in lithium niobate is asymmetrical in depth. However, by taking advantage of the several fabrication parameters, titanium-diffused waveguides with a mode intensity profile well matched to that of typical single-mode fiber are possible. Indeed, fiber-to-waveguide coupling loss as low as 0.3 dB (6%) has been achieved. Devices with total fiber-coupled insertion loss as low as 1.5 dB (70% intensity transmittance) have been realized (*4*). These very low losses have been achieved only recently (3 years ago losses of 8 to 10 dB were more typical) and have greatly enhanced the practical applicability of titanium-diffused lithium niobate integrated-optic devices.

Directional Coupler Switch

An important building block element for integrated-optic switches, and a variety of other devices, is the directional coupler (Fig. 2), which is a pair of strip waveguides closely spaced over an interaction length L. The spacing between the waveguides is comparable to the waveguide width, so that the evanescent tail of the mode profile of each waveguide extends into that of the other. As a result light guided in the two waveguides interacts, or is coupled. Light injected into one waveguide gradually "leaks" (or is coupled) into the second as it travels along the waveguide. This is a distributed coupling, and the net effect is strong only if light coupled to the second waveguide at each point along their interaction length is in phase with light that has coupled at an earlier point. To achieve significant coupling between the waveguides, the speed of light in the two waveguides must be the same. In this case the coupler is referred to as being phase-matched, and all of the light injected into one waveguide will be coupled to the second after a characteristic interaction length referred to as the coupling length.

The directional coupler can be easily understood by comparing it to a coupled pair of pendulums. Consider two pendulums having equal periods that are connected or coupled transverse to their common direction of motion. If only one is started swinging, slowly the second one begins to swing. After a characteristic time, all of the energy is transferred to the second pendulum. Indeed, in an identical time period, the kinetic energy will be transferred back to the initial pendulum while the second stops. The situation is oscillatory until friction damps out all motion. In the directional coupler, given enough interaction length, light will also periodically transfer between the initial and second waveguide along the length of the coupler. Typically the device is made to be one coupling length long such that light injected into one waveguide exits from the other.

In the case of the coupled pendulums, of course, if the characteristic periods are sufficiently different, there is no coupling of energy between them, despite a coupling element. Similarly, there is no net coupling of light between the two waveguides, in spite of their close proximity, if the refractive indices, and therefore the speed of light in the two waveguides, are sufficiently different. In this case, light injected into one waveguide exits from the same waveguide. By using an electro-optic material like lithium niobate for the substrate, we can introduce this refractive index difference or mismatch dynamically by the application of a voltage to electrodes placed over or along the waveguides. The routing of light between two alternate paths is therefore controlled by voltage.

The directional coupler operation can be described quantitatively by the solution to the well-known coupled mode equations (*5*). For input to one waveguide, and under the assumption of no loss, the crossover efficiency, η, to the second waveguide can be written as

$$\eta = \frac{1}{(1 + \delta^2/\kappa^2)} \sin^2 L(\kappa^2 + \delta^2)^{1/2} \qquad (1)$$

where κ is the coupling coefficient per unit length, and δ is the phase mismatch between the two waveguides. The value of κ depends exponentially on the interwaveguide separation normalized by the mode diameter, which in turn depends slightly on the wavelength. The coupling length for which complete crossover occurs for no index mismatch ($\delta = 0$) is equal to $L = \pi/2\kappa$. For the electro-optically controlled switch, δ depends on the induced index change, which depends in turn on the applied electric voltage (Fig. 2). The scale of the voltage axis depends on the electro-optic material, device length, and optical wavelength. In lithium niobate directional couplers 1 cm long, the voltage swing from complete to zero interwaveguide transfer is $\sim$2 and 8 V for wavelengths of 0.6328 (red) and 1.3 μm, respectively. These voltages are many times smaller than those achievable in bulk (non-waveguide) devices in the same material. This voltage reduction is a result of the small lateral dimension over which the electric voltage is applied and of the long interaction length, which is not limited by diffractive spreading as in the bulk case. The switch voltage decreases linearly as the coupler length is increased. The switching can be either discrete between the two outputs (cross talk as low as -30 dB has been achieved) or

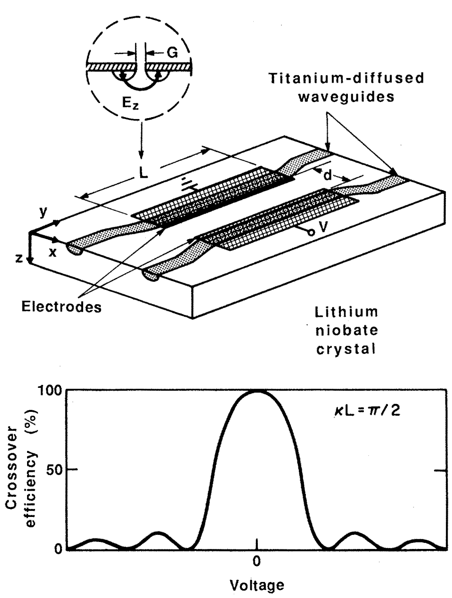

Fig. 2. Optical waveguide directional coupler switch in lithium niobate. The lower curve shows the qualitative switching response.

continuous (Fig. 2). Therefore, the switched directional coupler can also be used as a voltage-controlled tap or power splitter.

The electro-optically induced index change, Δn, depends on the refractive index, n, of the material; the applied electric field; and, most importantly, the electro-optic coefficient of the material, r. The material-dependent figure of merit is n^3r. For a fixed device length, the switching voltage scales inversely with this value. This figure of merit for lithium niobate is about six times that of GaAs or InP.

Switching Speed

Electro-optic switches can be made with very short switching times. The inherent response time of the electro-optic effect in lithium niobate is less than 1 psec (10^{-12} second). However, the practical switching speed is limited by circuit delays that result from the finite length electrodes required. For high-speed switching, two methods of electrical drive are used. In the simpler and slower technique, one views the electrode as a lumped capacitance. A resistor, typically 50 ohms, is placed in parallel to the electrode to impedance-match to the driving source. The switching speed is then determined by the resistance times the capacitance (*RC*) charging time. The capacitance depends on the electrode width-to-gap ratio and increases linearly with electrode length. The switching bandwidth for a 1-cm long waveguide switch in lithium niobate using a lumped electrode is 2 GHz. One can increase the switching bandwidth (speed) by decreasing the device length. However, as noted, drive voltage increases correspondingly.

For very high speed operation, the coplanar traveling-wave electrode is preferred. With this electrode configuration, the electrode is designed as a co-planar transmission line, impedance-matched to the driving source, and terminated with its characteristic impedance. In this case, the speed is not limited by capacitive charging times, but by "walk-off" between the copropagating optical and electrical signals that result if the two do not have the same propagation velocities. In lithium niobate, this walk-off limits the bandwidth of a switch 1 cm long to ~10 GHz, substantially higher than for lumped-capacitance electrodes. To achieve this limit it is important that the electrode be thick and highly conductive—gold is typically used—to minimize electrical propagation losses in the electrode. For GaAs and InP, the optical and electrical velocities are nearly equal, offering significant advantage for very high speed applications (*6*).

High-Speed Switch Applications

One interesting application of high-speed switches is to do optical time division multiplexing and demultiplexing in which several lower data-rate channels are temporally interleaved or separated, respectively. This technique, which is common at microwave frequencies, seems especially promising at optical frequencies because of the very broad bandwidth capability of optical fiber. The high-speed capability of traveling-wave directional coupler switches is illustrated in the time-division demultiplexing experiment shown in Fig. 3 (*7*). In this demonstration three optical pulse trains, each composed of optical pulses 50 psec wide and separated by 1 nsec (corresponding to a 1-Gbit/sec data rate), were combined with a much smaller interpulse separation. Three pulses of the multiplexed pulse train with 150-psec separation, as measured with a very fast optical detector and displayed on a sampling oscilloscope, are shown in Fig. 3. This pulse train is coupled to the high-speed optical switch, which is synchronously driven by a periodic electrical pulse train. The center pulse can be extracted without disturbing the neighboring pulses (Fig. 3). The multiplexed data rate in this example was about 8 Gbit/sec. The experiment was repeated at multiplexed rates as high as 10 Gbit/sec. No available electrical circuits can process or decode such high-bit-rate channels. Without optical demultiplexing, such closely spaced bits would simply be lost. However, by using fast optical switches, one can catch these otherwise unresolvable bits and demultiplex down to several lower data-rate channels (1 Gbit/sec in this example), which can be comfortably handled by conventional electronics.

A more near-term application for high-speed optical waveguide switches is as an on-off modulator for digital signal encoding (electrical to optical transducer) in lightwave communications systems. Light from a continuously running semiconductor laser is coupled to the input waveguide. One output waveguide is coupled to the transmission fiber. The light sent down the fiber is chopped into encoded pulses in response to the encoded electrical drive signal. The semiconductor lasers that serve as sources for lightwave systems can be directly turned off and on by varying the electrical current that drives the laser. This is the method used in present systems (*8*). However, direct laser modulation can be a problem at high data rates over long transmission distances. For maximum loss-limited distance, it is necessary to use lasers that operate at a wavelength of 1.55 μm, for which silica fiber has its lowest loss. However, for standard fiber, dispersion is finite in this wavelength region—that is, the optical propagation velocity depends on wavelength. To avoid the resulting pulse spreading in the fiber, which limits achievable transmission distance, the light source must emit at a single, fixed wavelength. Unfortunately, when semiconductor

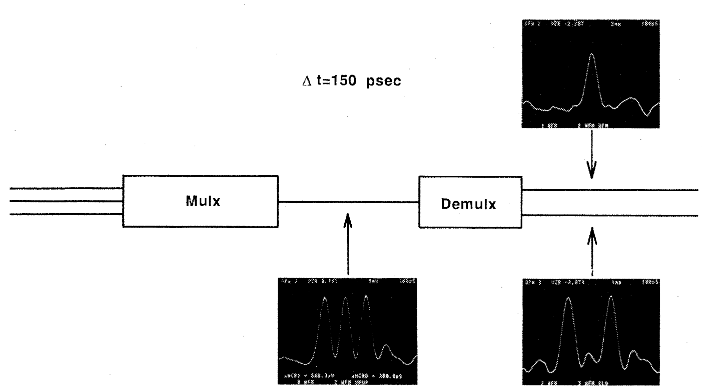

Fig. 3. Time-division multiplexing (Mulx) and demultiplexing (Demulx) with a traveling-wave optical directional coupler switch. The pulse separation is 150 psec.

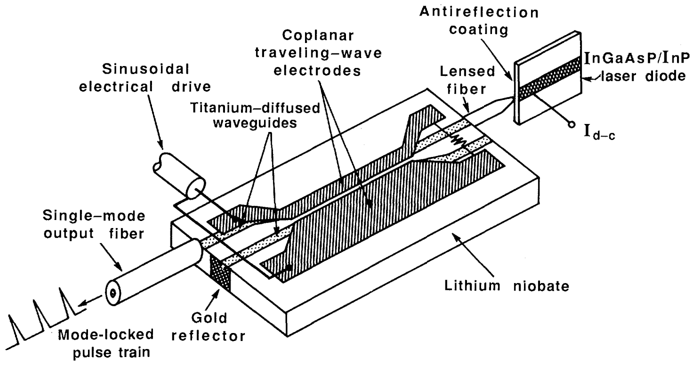

Fig. 4. Schematic drawing of composite cavity semiconductor laser with an intracavity waveguide switch.

lasers are turned on and off at high bit rates (greater than ~2 Gbit/sec), the wavelength emitted varies or chirps as the current pulse turns the laser on and off. Pulse spreading through dispersion on this chirped output limits the achievable transmission distance.

No such problem is encountered when the laser is left continuously on and the light is rapidly intensity-modulated with an external device. The advantage of waveguide external modulation over direct modulation for long-distance optical transmission at a high bit rate was demonstrated in two experiments in which a titanium-diffused lithium niobate directional coupler switch was used as an external modulator. In the first, information at a data rate of 4 Gbit/sec was transmitted over a distance of 117 km (*9*) and with a very low error rate (less than one error in 10^9 bits). This result surpassed, by 15 km, the distance achieved in a similar experimental lightwave system that used a directly modulated laser. More recently, information at a rate of 8 Gbit/sec has been sent over 68 km (*10*). An 8 Gbit/sec data rate is the equivalent of 125,000 simultaneous voice channels. At this rate the entire contents of the *Encyclopedia Britannica* could be transmitted in less than 0.1 second.

A low loss directional coupler switch has also been used to make an interesting hybrid composite lithium niobate–semiconductor laser (Fig. 4). A semiconductor laser, with one mirror facet coated to stop reflection so that it no longer had sufficient feedback reflection to generate light, was coupled to one input waveguide of a very low loss titanium-diffused lithium niobate switch. At the output end of the coupler, a gold mirror was deposited on the end of the crossover waveguide and the incident waveguide was permanently attached to a single-mode fiber. When the switch voltage is adjusted such that light transfers to the second waveguide, the light is reflected back to the gain medium (the antireflection-coated laser diode), and the composite structure forms a laser. The percentage of light tapped out of this composite—lithium niobate waveguide plus semiconductor gain element—cavity, can be controlled by the switch. By turning the switch on and off at a period corresponding to the duration of the round trip, this composite cavity can produce a train of short (~15 psec) pulses at repetition rates as high as 7 GHz by a process called "modelocking" (*11*). Such pulse trains are required for optical time-division multiplexing. This device serves as an example of the potential of monolithic integrated optics. There would be many advantages if the gain medium, the low-loss directional coupler switch, and a high-frequency amplifier to drive the switch could all be made on the same semiconductor substrate.

For typical switching applications in which a larger number of interconnections are required, several directional coupler switches can be cascaded onto the same substrate (*12*). Optical switch arrays with as many as 64 directional coupler switches have been integrated on a single lithium niobate chip to interconnect eight input fibers with eight output fibers (*13*).

Waveguide Filters and Polarization Splitters or Controllers

The waveguide directional coupler is versatile. By appropriate design, it can be made to function, for example, as a polarization splitter or as a tunable wavelength filter. Polarization-selective coupling can be achieved by using both the material and waveguide anisotropy to make κ, δ, or both depend on polarization. As a result, light polarized in the plane of the crystal, for example, transfers to the second waveguide, whereas that polarized perpendicular to the plane remains in the incident waveguide. Cross talk of the unwanted polarization in either output arm can be as low as 0.3% (−25 dB).

The wavelength-selective directional coupler (Fig. 5) relies on waveguide effects to make the effective refractive index difference between the two waveguides depend on wavelength (*14*). This is accomplished by making both the widths and the refractive indices of the two waveguides different. One waveguide is narrower than the other, but has a higher refractive index. The effective refractive index or velocity seen by the guided light is a weighted average of the actual index seen by the mode distribution. Most of the optical guided-mode energy sees the waveguide index except for the evanescent tails of the mode which extend into the substrate. The degree of confinement, and hence the effective index, depends on wavelength—the shorter the wavelength the tighter the confinement. Because the modal confinement also depends on the index difference and waveguide width, the effective index versus wavelength (dispersion curve) dependence for these two waveguides differs. Hence, for most wavelengths, the two waveguides are strongly mismatched and there is no net coupling between the two waveguides. However, by proper design, the dispersion curves for the two waveguides intersect at a desired wavelength. At this wavelength, the coupler is phase-matched, and complete light transfer to the second waveguide is possible. The phase mismatch increases approximately with the wavelength difference from the phase-matched value. Therefore, the filter response (crossover efficiency versus wavelength) is functionally the same as that of Fig. 2, with wavelength replacing voltage for the abscissa. Absolute filter width decreases as the coupler length or index difference between the two waveguides increases. With titanium-diffused lithium niobate devices, filter bandwidths of 200 and 700 Å have been achieved in the visible and infrared regions of the spectrum, respectively.

Application of voltage to electrodes placed over the waveguides changes the waveguide indices, which shifts the dispersion curves, resulting in a different phasematch wavelength. Thus, the device can serve as a tunable filter or as a wavelength-selective switch modulator (Fig. 5). Light at wavelengths of 1.32 and 1.55 μm is inserted into the lower waveguide. The electrode is biased to a voltage that allows transfer for the longer wavelength and is driven with a 10-V square-wave signal. In the experiment, a detector was placed at the output side of the incident waveguide. For all voltages the coupler is mismatched for λ = 1.32 μm, and light of this wavelength stays in the input waveguide as shown on the oscillogram in Fig. 5. However, light at λ = 1.55 μm switches between the two output ports in response to applied voltage. The switch is transparent to wavelengths other than those centered around the bias-selected value (1.55 μm in this case), which can be tuned at a rate of ~100 Å/V.

Wavelength-selective switches of this type could be used in wavelength multiplexing, in which light at several different wavelengths, each separately encoded, is sent down the same fiber and then separated before being detected and decoded. It may also be useful in more sophisticated distribution systems in which interconnection could be reconfigured on the basis of carrier wavelength.

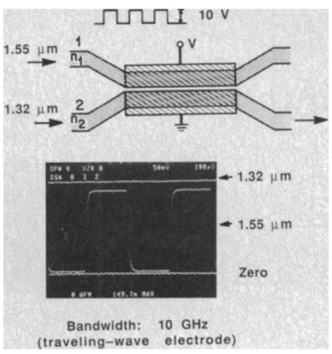

Fig. 5. Electrically tunable wavelength-selective directional coupler switch. The oscilloscope trace shows the detected optical output at the bottom waveguide for light at wavelengths of 1.32 and 1.55 μm incident in the bottom. The light at 1.32 μm remains in the bottom waveguide while that at a wavelength of 1.55 μm switches between the two waveguides in response to the 10-V voltage swing.

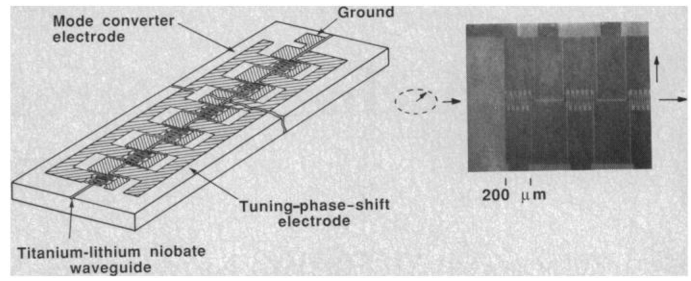

Fig. 6. Waveguide electro-optic polarization controller: schematic (left) and photomicrograph (right).

Although optical switch modulators, including wavelength and polarization selective ones, belong to an important class of guided-wave optical devices, that class is by no means the only one. A large family of integrated-optic devices has been developed, particularly by the titanium-diffused lithium niobate technology, which can be used for both optical communications and signal processing. One further example, which differs from the directional coupler, is the lithium niobate waveguide electro-optic polarization controller shown in Fig. 6 (*15*). This device performs the function of electrically controlled polarization transformation. By the application of an appropriate voltage to the two separate electrodes, an arbitrary (in general, elliptical) input polarization can be converted to any desired output polarization. The required voltages depend on both the input and the desired output polarization. Devices that perform polarization control are required in optical fiber systems such as heterodyne detection systems where the polarization of the received signal must be the same as that of the local oscillator to allow efficient mixing. Typical single-mode fiber does not maintain the polarization state which, in fact, tends to change in time. By using a device such as that in Fig. 6, the polarization of light from the local oscillator can be dynamically changed to match that of the received signal.

The polarization transformer is a single waveguide with two separate but intertwined overlaid electrodes. A general elliptical polarization state can be decomposed into components in and perpendicular to the plane of the wavelength substrate. The relative amplitudes of these two components, as well as their relative phase, are the two parameters that define the polarization state. The interdigitized finger electrode sections (Fig. 6) change the relative polarization amplitudes in and perpendicular to the device substrate plane, while voltage to the uniform electrode section changes their relative phase. The interdigital (periodic) electrode allows effective coupling between these two polarizations in spite of significantly different refractive indices resulting from the birefringence of lithium niobate. The electrode period, which is dictated by birefringence and wavelength, is 7 and 18 μm for operation at 0.6000 (red light) and 1.3 μm, respectively. For the application described above, a feedback loop is required in order to generate the voltages to control the polarization transformation. The polarization splitter described above can be used to measure the polarization in such a feedback loop.

A variety of other waveguide devices including interferometric modulators (*16*), *Y*-branch splitters, narrowband reflection filters (*17*), phase modulators, frequency shifters (*18*), ring resonators, and more have been demonstrated. Indeed, the feasibility of single-chip processors such as the radio-frequency spectrum analyzer (*19*) and a high-speed (10^9 samples per second) analog-to-digital converter (*20*) have been shown. Optical communications has been the driving force behind early integrated-optics research. However, as suggested by these last two examples, signal processing including possibly optical computation are also current and potential areas expected to feel the effects of optical guided-wave techniques.

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