A light source coupled to a photosensitive device in an opaque enclosure forms a 4-terminal network with a variety of useful electronic applications.

THE OPTICAL LINK:

A NEW CIRCUIT TOOL

By DONALD LANCASTER

PAIR a light source with a photosensitive device inside an opaque enclosure and you have an optical link, a new circuit tool that can perform many electronic functions impossible or extremely difficult by any other means. Optical links are now available commercially with frequency response from d.c. to 10 mc. and power control capabilities from a few milliwatts to 100 watts. Laboratory optical links are now working in the gigacycle region with extreme linearity and power densities.

What is so spectacular about a light bulb and a photocell? For one thing, a pair forms an ideal four-terminal network. The input and output are completely isolated. Any change of output termination is not reflected at the input. Output and input may be at quite different supply levels, to 20 kv. or more if necessary. There are two independent signal paths in cascade, an electrical one and an optical one. Any circuit function may be performed on either signal path with absolutely no interaction. The devices are entirely resistive and contain no transient-producing reactances. From d.c. to cutoff frequency the amplitude and phase response is perfectly flat. When used as a switch, there is no contact bounce, key clicks, or other transient—just a smooth transition from an "on" to an "off" state. The device can act as an amplifier, integrator, control, multiplier, or transformer. Optical links can be made self-indicating, acting as readouts or indicators.

Optical links have become practical due to the tremendous advances made recently in the available light sources and photoconductors. Several dozen firms now offer optical links commercially, ranging in price from a $4.00 unit intended specifically for tone switching in electronic organs, through multi-pole relays and electronic choppers, to $100.00, 10-mc. bandwidth units. A versatile link that exhibits a 2-watt control capability and a response time of a few milliseconds, can be built by any experimenter for around 85 cents.

Available Light Sources

The characteristics of an optical link are determined by the light source, the geometry, and the photodetector. An obvious light source is the incandescent lamp. These are low in cost, readily available, and have a wide spectral output. The rise time is extremely poor, on the order of 100 msec., thus limiting incandescent links to d.c. and low-frequency audio applications. They are highly non-linear and subject to vibration and burnout. They are compatible with the voltages and currents common to transistorized circuitry.

A second low-cost source is the neon lamp. Above a threshold value, the light output *vs* power input is very linear. Response time is a few microseconds. A photodetector with a good orange response must be used since neon output is primarily limited to two orange spectral lines. The maximum available output is somewhat limited which, in turn, limits the control capability of the optical link. At least 60 volts of control voltage are required, but the input power is generally much less than required for incandescent sources.

Electroluminescent devices offer a uniform light output with millisecond response time, but they are highly frequency-dependent and have a limited light output. They will not work at all with a d.c. input.

A new and quite promising light source is the injection diode, a class of semiconductor which produces light output in direct proportion to a forward bias current. A nanosecond rise time is combined with a wide dynamic range and good linearity. Light output is typically in the infrared region (9000 Å) requiring a detector with good infrared response. The light output is almost a point source (20 mils or so) and emission is in one direction only. A light pipe consisting of fiber optic bundles may be used to conduct virtually all the light produced to the photodetector end of the link. This can be quite important since some detectors have very small effective areas. These new devices are still rather expensive, costing from $25 to $100 in small quantities.

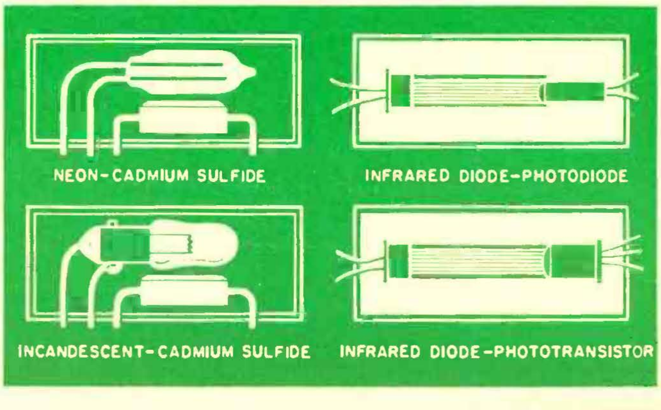
The gas or ruby laser offers an intriguing light source for laboratory optical links, providing coherent, monochromatic light at extreme power densities. Lasers can produce light power densities so powerful that dielectric breakdown of the air can occur if the normally collimated laser beam is focused to a point. Coherent light is much like a crystal-controlled r.f. source. A laser's output can be modulated with hundreds of gigacycles of signal bandwidth. The high cost of such devices generally precludes their use in all but lab devices at present, but this source holds great promise for the future.

Types of Photodetectors

An optical link must have input and output matched. It would be rather foolish to drive a nanosecond photodetector with an incandescent lamp that has a frequency response of 20 cps at best. Similarly, a wide-area light source would lose most of its energy trying to drive a small photojunction device, unless all the output light is somehow gathered and focused into a useful position.

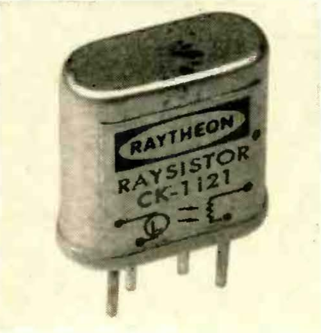
For low-frequency applications, the cadmium-sulfide and cadmium-selenide photoresistors are preferred. They are low in cost, have a large surface response area, and can control considerable power. They are bilateral, operating equally well from a.c. or d.c. input current. The resistance value is constant and independent of the applied voltage.

Fig. 1. Types of commercially available optical links.

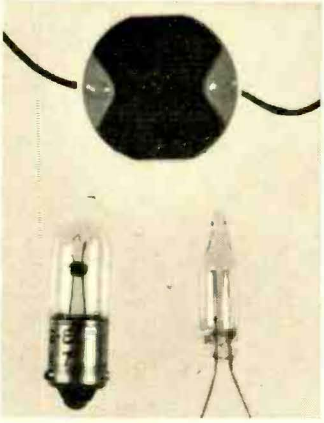


The Allen LR-1 is a fairly inexpensive incandescent optical link that is used for tone switching in electronic organs.

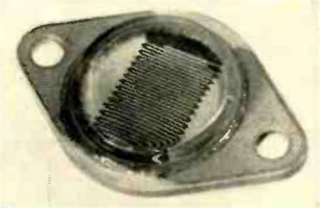
This compact Sigma unit serves as a d.p.s.t. relay that has millisecond response time.



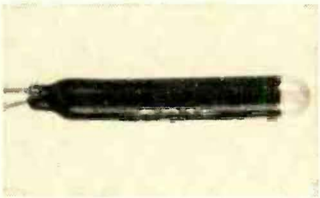
Raytheon has a line of general-purpose optical links that include both neon light and incandescent light sources.



An experimenter's optical link costing under a dollar can be made from a Sigma 5HC1 photoresistor and either an NE-2H neon bulb or a type #47 pilot bulb. Link can control 2.4-watt load at up to 300 volts peak.



The Delco LDR-25 light-dependent resistor may be employed in an optical link to allow 100 watts of control power.



A silicon photodiode, such as this Texas Instruments Type H-60, may be utilized in an optical-link arrangement.

As specific examples, the *Sigma* 5HC1 is a 600-mw., 300-volt unit costing 75 cents singly. It has a rise time of 3 msec. and a fall time of 25 msec. A second unit is the *Delco* LDR-25, a 25-watt, 200-volt, $1.50 device. The power-handling ability of any control resistor is equal to four times its dissipation when driven from a constant-voltage supply. These two photoresistors can control 2.4 and 100 watts respectively. The fastest available units of this type turn on in considerably less than a millisecond and turn off in 1 or 2 milliseconds.

Solar cells are detectors that offer a unique advantage. They produce an output voltage on their own, requiring no additional power supplies for the load. One-tenth microsecond rise time is combined with fairly low cost and good linearity. Their efficiency is very low and the output power available is, at best, a few milliwatts, limiting their present commercial use.

The photodiode is finding wide application in high-frequency linear optical links. These devices are reverse-biased *p-n* junctions that produce microampere-sized currents in linear proportion to the incident light. The frequency response of some units is good to the gigacycle region, with corresponding nanosecond rise times. Prices start at around $4.00. A typical unit is the *Texas Instruments* Type H-60 which produces a maximum light current of 200 μa. when biased between 10 and 50 volts. It responds to beyond a megacycle and is quite small, measuring 70 mils in diameter by ½ inch long. For useful control output, the light current must be amplified by a transistor or two to a useful power level.

A phototransistor is a photodiode with a built-in gain of as much as several hundred. The best rise times are longer than a straight photodiode. They are somewhat more expensive.

The photo field-effect transistor is a brand new device with tremendous light sensitivity, good linearity, and fast response time. As yet, this device is too new and too expensive for widespread use, but it should become an important photodetector.

The method of specifying just how a photodetector will perform is a figure of merit called the *quantum efficiency*. This is simply a ratio of input photons to output electrons. If 1000 photons of incident light produce 1000 electrons, the quantum efficiency is 1.0. The cadmium-sulfide photoresistors have an efficiency of around 1,000,000. The photodiode and solar cell are very much poorer, having quantum efficiencies of 0.5. A phototransistor has an efficiency of 100 or so. The new photo field-effect transistor can exhibit quantum efficiencies of several *billion* under certain circumstances, making this device the most sensitive known.

Commercially available optical links take one of the two general forms shown in Fig. 1. The first form pairs an incandescent or neon bulb with a cadmium-sulfide photoresistor to provide a low-frequency, high-power control device. Prices start at $4.00 each. Typical units are shown in the photos. Incandescent bulbs are used for "on-off" power control at very low frequencies, while the neon units serve well for more linear applications at higher frequencies. Although higher voltage (at least 60 volts) is normally required for the neon units, they draw considerably less power.

The second form pairs an injection diode with a *p-n* photodiode or phototransistor, giving a more expensive ($100 to $250) device that serves as isolator or linear amplifier up to 10 mc. The controlled power is considerably less than the low-frequency units.

Table 1 lists a few of the commercially available optical links and their manufacturers. The table is by no means complete, but at least one of each general type of optical link is listed as representative.

There are two present limitations to the widespread use

Table. 1. Some commercially available optical links.

Manufacturer	Model	Type	Cost	Application
Allen Organ Co. Macungie, Penna.	LR-1	I/C	$4	Tone switching in electronic organs; remote controls.
General Electric Co. 1 River Road Schenectady 5, N.Y.	PC-L	I/C N/C	$8	General-purpose line of electrically variable resistors.
Hewlett-Packard Assoc. 620 Page Mill Road Palo Alto, Calif.	HPA-4301	D/P	$145	10-mc. wide photon-coupled isolator.
Raytheon Industrial Comp. Div. 55 Chapel Street Newton 58, Mass.	CK1121 CK1124	I/C N/C	$4 $4	Full line of low-frequency optical links. Various packages.
Sigma Instruments Co. 70 Pearl Street South Braintree, Mass.	4L2N	N/C	$5	D.p.s.t. relay. Four-pole models also available.
Texas Instruments Semiconductor Div. Box 5012 Dallas 22, Texas	PEX-3002	D/P	$275	Electronic chopper. Cut-off frequency is 30 kc.

Light Sources: D—infrared diode; I—incandescent; N—neon.

Detectors: C—cadmium sulfide; P—"p-n" photodiode.

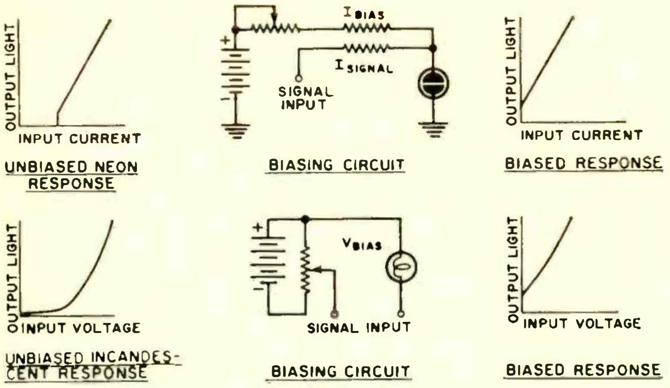


Fig. 2. Bias may be added to low-frequency optical-link light sources in order to improve their linearity and sensitivity.

of optical links. The first has been the unrealistic pricing of some of these devices to date, primarily due to low volume and lack of applications. Since it is now possible to build a low-frequency optical link for one-fifth the cost of equivalent commercial units, the commercial prices will certainly drop. The injection diode and the *p-n* photodiode are still new devices that have not as yet achieved the high-volume, low-cost status of many of today's semiconductors. The low-frequency optical links will be drastically reduced in price in the near future, while the higher performance devices will trend downward in price over the next five or six years. Both types should ultimately become low-cost volume devices.

A second problem is the poor linearity of the low-frequency optical links. A neon lamp is linear only after ionization; a threshold exists up to the ionization current. Incandescent lamps are highly non-linear, due to a change in efficiency of radiation as the filament temperature is changed. Bias may be used to advantage to linearize either light source, as shown in Fig. 2. In the neon units, a current bias is provided to keep the neon ionized at all times. The signal then adds to this ionization level, producing a linearized output. Voltage bias is used with the incandescent bulbs to keep the filament moderately visible at all times. The input signal again adds to the brightness level, giving an output more in proportion to the drive signal. The price paid for biasing is a reduced change in resistance ratio at the output.

Applications

There are many uses for optical links. Perhaps the simplest application is an isolated remote-control switch. The "off" resistance of a cadmium-sulfide cell is several megohms; the "on" resistance is between 10 and 100 ohms. In operation, the exciting lamp is turned "off" or "on" which then turns the output "off" or "on." This is most useful in electronic-organ tone switching where transients and key clicks must be eliminated. The isolation allows a low-voltage or low-current remote control totally independent of the controlled signal, useful for many other "off-on" applications. Fig. 3A.

There is no reason to limit one source to one detector, for either may be used in multiples. A multi-pole, single-throw noiseless relay results from a single neon or incandescent lamp driving two or more photoresistors in a single package (3B). Logic functions are a natural extension of this. For instance, any number of detectors may be placed in series. Unless all are illuminated, the output will remain in a high-resistance state, producing an *and* circuit (3C). An *or* circuit is obtained by exciting a single detector with multiple sources. Any source that is "on" will excite the output which, in turn, assumes an "on" or low-resistance state (3D).

Any logical decoding operation may be obtained by using a multiplicity of sources, masks, and detectors. A decimal-to-binary converter requires 9 lamps and 4 detectors. A "3" excites only lamp #3 which illuminates the 2^0 and 2^1 detectors, but not the 2^2 and 2^3 detectors, forming an 0011 binary output (3E).

If a square-wave input is fed into an optical link, the output will follow an "off-on-off-on" sequence, making an excellent chopper for low-drift d.c. amplifiers and other uses. A slowly varying d.c. input signal may be chopped up by the optical link, fed to a gain-stable a.c. amplifier, and then detected and filtered. The output is the input d.c. signal,

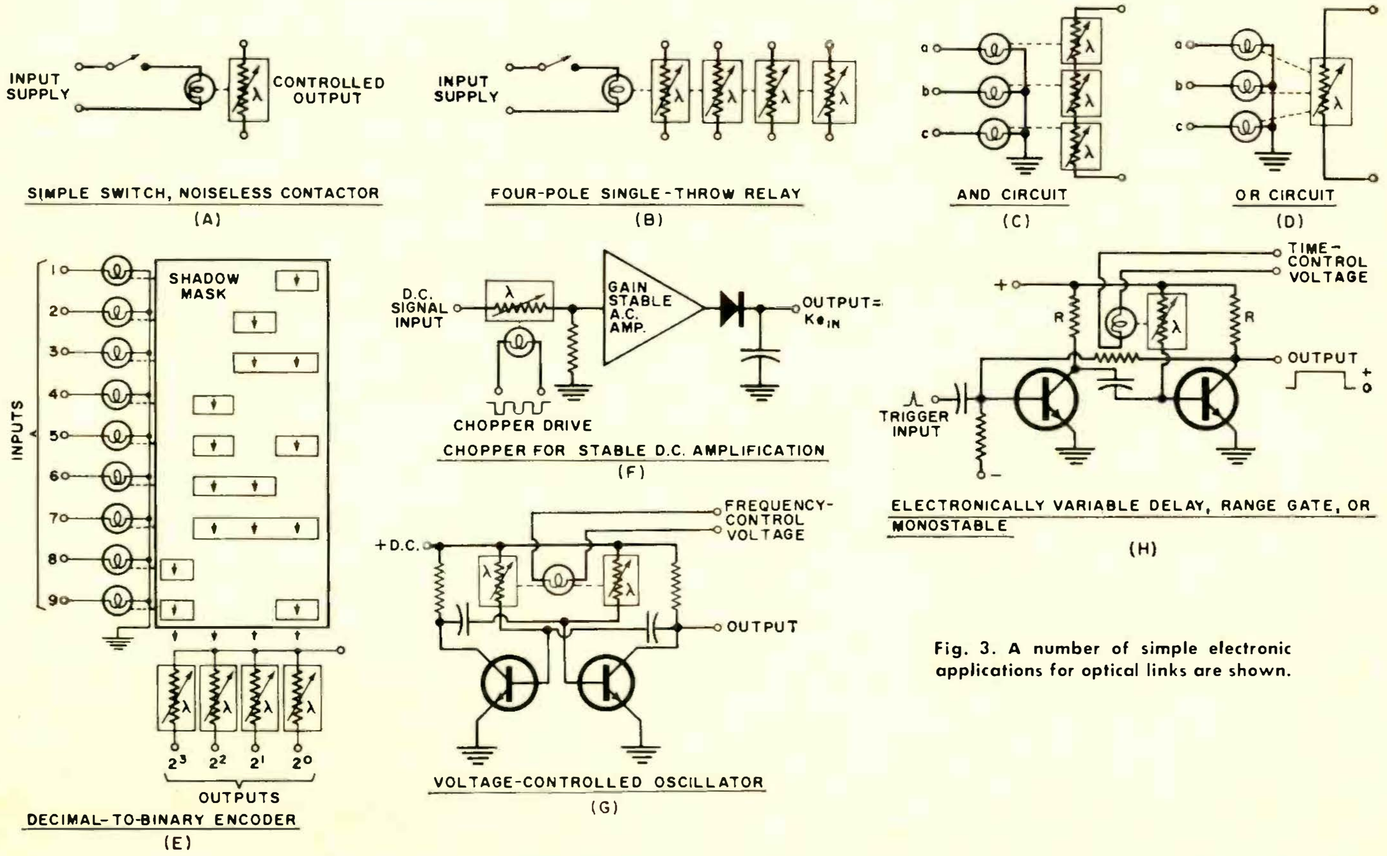


Fig. 3. A number of simple electronic applications for optical links are shown.

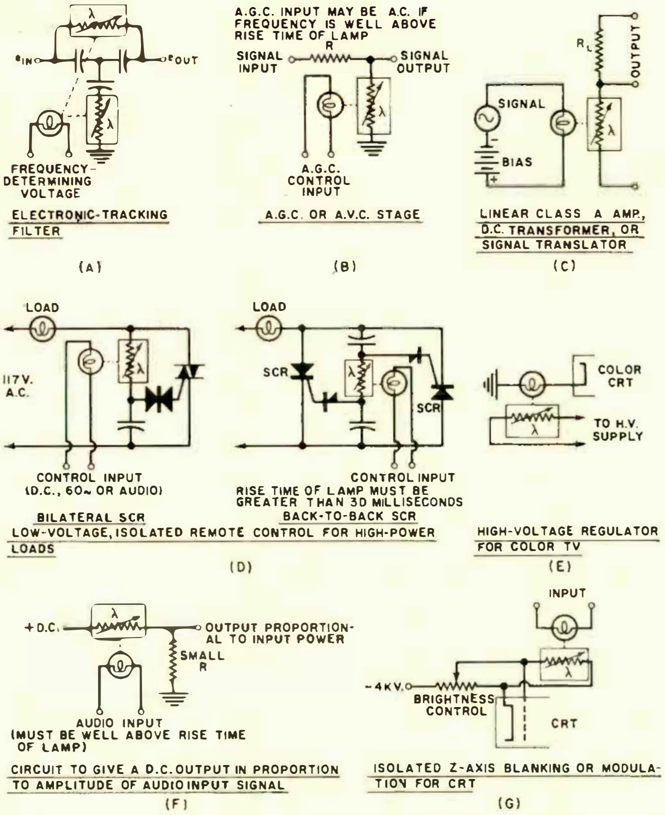


Fig. 4. Additional applications discussed in the text.

highly amplified and drift-free (3F). An optical-link chopper using cadmium-sulfide cells has no d.c. offset term, no switching noise, no transients, and is wear free. The chopping drive is isolated from the input signal.

The simplest linear mode of operation uses the optical link as an electrically variable resistor. One application is a voltage-controlled oscillator where the optical link forms an electrically variable multivibrator. Two optical links are used to replace the normal timing resistors in an astable multivibrator. Varying the control voltage varies the frequency of the multivibrator by changing the *RC* charging time (3G). If only one optical link were used, a symmetry-modulated rectangular-wave generator would result (3H). By replacing the resistors in a bridged-T filter, the rejection frequency may be varied, forming an electronic-tracking filter (Fig. 4A).

The purely resistive nature of the optical link makes it ideal for a.v.c. and a.g.c. systems. A control signal can alter the gain of an electronic system without affecting the bandwidth or bias of any signal stages. Total isolation of a.g.c. and system signals is maintained (4B).

The signal need not be d.c. With an incandescent link, the bulb cannot follow 60 cps and higher power variations and lights to an average value in proportion to the input power, thus setting an output resistance value that only follows the average value of the input and not the input itself (4F).

This same technique comes in handy in SCR dimmers and power controls. The normal timing resistor in the SCR control is replaced by an incandescent optical link, driven by a low-voltage, line-isolated 60-cycle or d.c. source (4D). An important application is in theater lighting where doorbell circuitry can provide long remote-control runs for high-power lights. Similarly, the bulb may be excited by an audio source to allow audio control of lights. This technique completely isolates the input audio from the a.c. line and the controlled output.

There are many circuits that take an audio signal, amplify it, emitter follow, filter, rectify, and then filter again to obtain a slowly varying d.c. output in proportion to the power present in the input audio signal. Examples are in tone signalling, music analysis, voice controls, alarms, and commercial killers. A single optical link will replace all these parts. Input audio is used to excite the source. The output resistance variation will follow the input power level smoothly as long as the audio frequency is well beyond the response time of the source or detector.

Below its cut-off frequency, an optical link makes a linear amplifier that can exhibit substantial power gain. This permits signal translation between two systems with no interconnection except a beam of light. The optical link also serves as a wideband transformer having no reactance or resonances and a response from d.c. to its cut-off frequency (4C).

A number of specialized circuits are of interest. Two involve the use of an optical link to control a signal at a supply voltage several kilovolts different from the control signal. One of these is in a color-TV set. The CRT cathode current may be used to excite an optical link which serves as the high-voltage regulator, increasing the horizontal drive as the beam current goes up (4E). Oscilloscopes usually require expensive high-voltage capacitors to couple signals, blanking, and modulation to the grid and cathode. The time constants can prevent very low-frequency or d.c. Z-axis modulation. This is simple for an optical link. The link is put in parallel with the brightness control and is driven by the Z-axis input (4G).

The brightness variations of a light source occur at *twice* the frequency of the supply, since maximum power is delivered both on negative and positive signal peaks. This allows an optical link to be used as an untuned frequency doubler (Fig. 5A). Any number of stages may be cascaded to provide frequency multiplication of 2, 4, 8. . . . The upper limit is determined by the cut-off frequency of the optical links used.

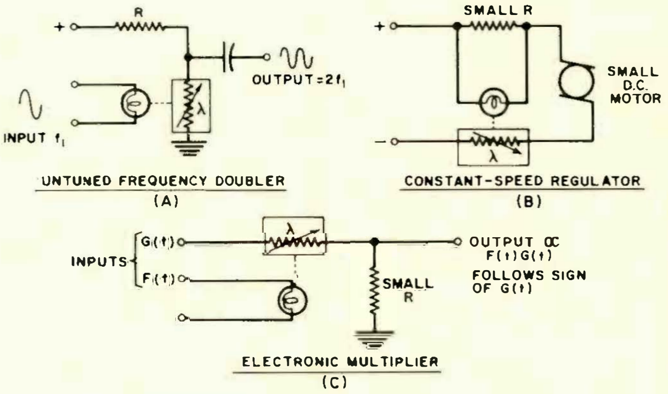


Fig. 5. Optical links as doublers, regulators, multipliers.

The power optical link can form an efficient regulator for small series d.c. motors, allowing constant-torque or constant-speed operation. Usually the back-e.m.f. of the motor is used to drive an optical link which, in turn, regulates the motor current (5B).

Cadmium-sulfide optical links have another interesting application which makes use of the fact that their output is a constant resistance independent of the polarity and magnitude of the signal across their terminals. If such a link is driven by a signal *G(t)*, the output will be the product *F(t)G(t)*. This is a two-quadrant multiplier that follows the sign of *G(t)* (Fig. 5C). Unlike most electronic multipliers, substantial output swings may be obtained at useful power levels. The maximum permissible frequency of *F(t)* is determined by the link response time, but *G(t)* may be any frequency. For instance, in an incandescent link *F(t)* would have to be less than 20 cps, but *G(t)* could be 10.7 mc.

As the prices drop and more use is made of this powerful new circuit tool, the optical link will emerge as an important, low-cost electronic control component. ▲