LIGHT BEAM COMMUNICATOR

Build the Air Hop, an inexpensive system that communicates with light.

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IMAGINE YOU WERE CHALLENGED TO build a device that could send an optical audio signal—with a bandwidth of 300 to 3000 Hertz—as far as possible. To make the contest as fair as possible, the rules would require that only commonly available parts could be used. Also, because optics would play a large role in determining the range of such a device, no optics with a collection area greater than seven square inches could be used.

A dozen years ago, the author lost just such a contest by achieving a communications distance of a little over two and a half miles. The winning entry achieved a distance of 6 miles!

The optical communications system presented here is a somewhat modified version of the author's original Air Hop. The circuits have been redesigned in order to use common parts and provide a decent link at a reasonable cost. The unit has an output power of about 10 milliwatts peak and 5 milliwatts average. It uses frequency modulation on a 50-kilohertz carrier and has a bandwidth of 300–3000 Hertz. Without optics, the Air Hop can communicate about 40 feet—with 3-inch diameter optics (a magnifying glass), the range is increased to over a mile.

Air Hop can be used as a simple point-to-point audio communications system or to transmit digital data. Since its bandwidth is the same as a phone line, modems can be used to send and receive digital data. It can also be used as a link for a remote control such as that used in a TV receiver, perhaps with a tone encoder/decoder combination. A remote link to a repeater or a long-distance "broken beam" security system can also be made. Whether you need a link from a house to a barn or a short jump across the commotion of Wall Street, Air Hop can do it.

Electro optics

Before we get into the design and construction of the Air Hop, let's explain some optical terms.

PIN Diode. A photosensitive di-

ode with a response time of a few nanoseconds. It can be used in a photoconductive mode where the current through it is a function of light, or in a photovoltaic mode where the voltage across it is a function of light (see Fig. 1).

Phototransistor. A transistor whose base current is a function of light. The collector current is the base current times the gain of the device. Response time is a few microseconds.

Photodarlington. Two transistors in the same package connected in a Darlington configuration. The first transistor is a phototransistor and the second is an ordinary transistor. Response time is tens to hundreds of microseconds.

Detector area. The area (in square inches or millimeters) of the light-gathering detector. Most PIN diodes have a plastic case that acts as a simple lens and provides a collection area of 0.01 to 0.025 square inches. This area is important when you're calculating lens gain.

Inverse square law. This is the "killer" in nearly all communications systems. Very simply stated, it means that if you increase the distance between the transmitter and the receiver, the signal strength will drop in proportion to the square of the distance. For example, if you receive 9 microwatts of power when the distance between the transmitter and receiver is ten feet, you will receive only 1 microwatt of power if you increase the distance to thirty feet.

Transimpedance amplifier. An amplifier with a very low input impedance. Sometimes called current-to-voltage converters, these special amplifiers are often used in optical systems because their low impedance load will ensure maximum current from a photodiode. They can provide a bandwidth up to a few hundred megahertz.

Lens gain. The ratio of the lens area to the detector area. Since the area of a lens is larger than the area of the detector, more light is gathered by the lens. Lens losses and focusing errors (which together should be about 15%) must be included in a rigorous calculation of lens gain.

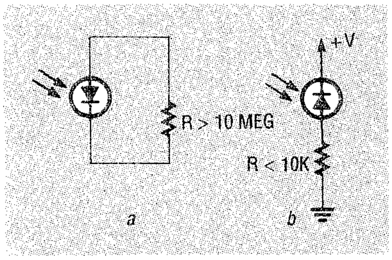

FIG. 1—A PHOTOSENSITIVE PIN diode has a response time of just a few nanoseconds.

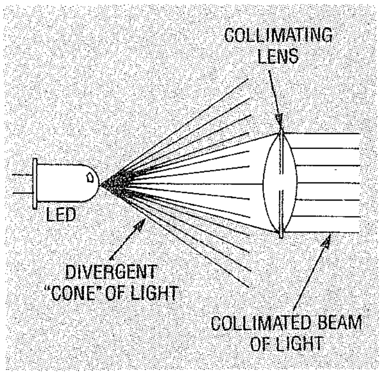

FIG. 2—THE LIGHT FROM AN LED diverges or spreads out as it leaves the LED. A lens will then collimate the light so that it travels in parallel beams.

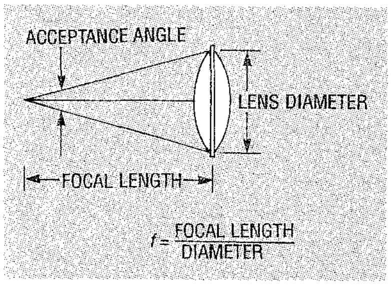

FIG. 3—THE f NUMBER or lens speed is the ratio of the focal length to the diameter. You can think of this as an optical acceptance angle.

Infrared. The region of the light spectrum next to the color red (about 800 nanometers). Most infrared LED's emit at either 880 nanometers or 940 nanometers. Most silicon detectors have their maximum response at about 900 nanometers. Infrared is used because most red (visible light) LED's have trouble producing a half a milliwatt of power, while many IR LED's have an output of 10 milliwatts or more.

Collimate. To direct in a straight line. When light from a source travels in parallel beams instead of a divergent cone, it is said to be collimated. Although you can't form a truly collimated beam, the lens on the transmitter attempts to do that (see Fig. 2).

Divergence. The "spreading out" of an optical beam. In other words, a divergent beam is the opposite of a collimated beam. All optical beams diverge, some more than others. If you could form a beam with zero divergence (you can't), it would not obey the inverse square law. In other words, you could send your beam an infinite distance because the energy wouldn't spread out. Laser beams have small divergence compared with other light sources. Spot lights are built to have a small amount of divergence, whereas flood lights are built to have a great deal of divergence (see Fig. 2).

Responsivity. A measure of the relationship between the optical and the electrical signal of a detector. A rule of thumb for PIN diodes is 0.4 to 0.6 amps per watt. This means that if 1 milliwatt of light strikes a PIN diode, a current of 0.4 to 0.6 milliamps will flow through the diode. To put that in perspective, Air Hop will work at levels of about 100 picoamps of current or about 200 picowatts of optical power.

AC and DC light. If you pulse an LED on and off it becomes an AC-light source. If you simply apply DC though it, it becomes a DC-light source. This concept is important because most light sources contain some AC and some DC light. Normal tungsten-filament light bulbs contain a lot of DC and some AC light (because of the thermal time constant of a hot filament). The sun contains a lot of DC *and* a lot of AC. Fluorescent lights contain some DC and a lot of AC. The only reason that this is important is that if you build a DC-coupled optical receiver and operate it outdoors where there is a lot of sunlight, the receiver can easily "saturate" and your AC signal will not be amplified correctly. Some kind of "light shield," such as those that are used on some camera lenses, will help. That's why the Air Hop uses an AC-coupled detector.

f number or lens speed. In lenses, the ratio of the focal length to the diameter is called the "f" number (f = fl/d). The smaller the number, the "faster" and more expensive the lens. It is convenient to think of this as an optical "acceptance" angle (see Fig. 3). This will be important in choosing the transmitter's collimating lens. In cameras, where the focal length is fixed, a lens with a larger diameter than another lens has a smaller "f" number, and is said to be faster. That's because the larger lens gathers more light and the shutter can be set to a faster speed than the smaller lens. Table 1 shows f numbers vs. acceptance angles.

Thermal noise. Although thermal noise is not applicable to optical devices such as lenses, the electronic performance of your optical system will be limited by thermal noise. Thermal noise is caused in an electrical device by the random movement of molecules. The thermal current noise (i_N) of a resistor is given by:

$(i_N)^2 = 4KTB/R$

where

K = Boltzmann's constant (1.38×10^{-23})

T = temperature in Kelvin (300)

B = bandwidth in Hertz

R = resistance in ohms

A 300K resistor operated at near room temperature in a receiver with a bandwidth of 20 kilohertz will have a thermal noise current of 33 picoamps

Although 33 picoamps might not sound like a lot of current, the noise it will cause at the output of the transimpedance amplifier will be about 10 microvolts (RMS). Converting to peak-to-peak noise gives about 60 microvolts peak-to-peak.

In the Air Hop, the only amplifier between the transimpedance amplifier and the comparator is a differential amplifier with a gain of about 50. That amplifies the 60 microvolts of noise and produces about 3 millivolts of noise at the output of the optical amplifier. Actual measurements showed 5 millivolts of noise. That is reasonable because there are other noise-producing devices in the system such as the current noise of the first transistor. Although every transistor produces some noise, the first one produces more because of its higher signal amplification.

TABLE 1
f NUMBER VERSUS ACCEPTANCE ANGLE

f	Angle (in degrees)
0.5	90
0.75	67.4
1.0	53.2
1.5	36.8
2.0	28
2.5	22.6
3.0	19
3.5	16.2
4.0	14.2

FM TRANSMITTER PARTS LIST

All resistors are ¼-watt, 5%.
R1, R5, R9, R15, R16—1000 ohms
R2—22,000 ohms
R3—10,000 ohms
R4—1000 ohms, potentiometer
R6—100 ohms
R7—5600 ohms
R8, R13—2200 ohms
R10—470 ohms
R11—50,000 ohms, potentiometer
R12—33,000 ohms
R14—15,000 ohms
R17, R18—22 ohms (see text)
Capacitors
C1–C3, C6—1 µF, 16 volts, electrolytic
C4—100 µF, 16 volts, electrolytic
C5, C9—10 µF, 16 volts, electrolytic
C7—0.001 µF, ceramic
C8, C10, C11—0.01 µF, ceramic
Semiconductors
IC1—NE555 timer
Q1–Q4—2N3904 NPN transistor
LED1–LED4—IR LED (Optek OP293A 880nm, Optek OP295A 880nm narrow beam, Lytron 940nm, see text)
Other components
MIC1—electret microphone
Miscellaneous: 4 "AA" batteries and holder, PC board, PVC pipe and plastic disks, hardware, wire, solder, etc.

One reason it's important to present equations like this is that they give us insight into system improvement. If there were no noise, virtually unlimited distances could be achieved. However, when the strength of the signal is less than the noise, we're out of luck. We can control temperature to some extent, and the equation shows that at a lower temperature, the noise is lower. But lowering the temperature of the transimpedance resistor even by 100 degrees Kelvin will decrease the noise power only by a factor of about 1.2.

If a system requires only a small amount of bandwidth, say a few hertz, as in a television remote control, we could decrease the bandwidth from 20 kilohertz to 20 Hertz and decrease the noise by a factor of about 30. Even with the inverse square law working against us, that would improve the range by a factor of about 5. Such a bandwidth reduction would require a good tunable filter, but it certainly can be done. Of course, audio signals sent over a link with a 20-Hertz bandwidth wouldn't be recognizable as audio. It would, however, permit Morse-code communication.

Photodetector. Any device that can convert light into an electrical signal. Phototransistors, photo SCR's, phototriacs photocells, solar cells, and photodiodes are all examples. Even photoresistors and thermocouples can be loosely considered as forms of photodetectors.

Phototransistors and photodarlington detectors are often used to detect light. Both work well if you don't require high speed. Typical phototransistor rise and falls times are 1 to 5 microseconds; for Darlingtons they are hundreds of microseconds. In electronics that is equivalent to measuring bandwidth with a stop watch and a calendar, respectively.

The author prefers to use PIN diodes in the photoconductive mode as detectors. Rather than being limited by the gain and bandwidth of a phototransistor, PIN's give us the choice of both by allowing us to design our own amplifiers. PIN diodes are also very "quiet." Their noise is almost unmeasureable.

LED's. A light-emitting diode is a semiconductor device that emits light when forward biased. You would think that choosing an LED for a system such as this would be a simple matter, but it's not. Characteristics such as power output, wavelength, speed, and beam angle all come into play.

The first consideration is usually the power output. However, if you can't get the power into your lens, it's simply wasted, and if it's at the wrong wavelength, your detector won't see it.

Wavelength is important. The most widely used wavelengths for infrared devices are 880 nanometers and 940 nanometers. The first choice is to find a detector and emitter that match. We used 940 nanometers, which is further into the infrared than 880. Many detectors made for 940 nanometers have a built-in visible-light filter. Filters are not often put on the 880-nanometer devices because that wavelength is near the visible spectrum and such a narrow filter would be difficult to produce in large quantities.

If you wish to produce a hundred thousand Air Hop systems with optics, you would want to buy emitters with wide but uniform beams. Then you would have a custom lens designed and produced at a small cost in plastic material. That would produce the most uniform beam and would be reproducible in large quantities. In applications such as remote control, you might want to use an emitter or many emitters to "flood" an area. In that case, you would want an emitter with a wide beam.

If, on the other hand, you're just trying to see how far you can "air hop" a signal, you will want something totally different. Narrow beam angles are necessary for efficient coupling to an off-the-shelf lens. As a matter of fact, choosing the smallest beam angle available will save money when it comes to buying a lens. The smallest easily obtainable beam angle for an LED is about 20 degrees. When a manufacturer specifies that angle, he really means a "half angle" of 20 degrees, or a solid cone of 40 degrees.

The angle also specifies the half-power point. For example, if a manufacturer specifies 5 milliwatts and a beam angle of 20 degrees, that means that if you can capture all of the power contained in a 40-degree cone, you will get 2.5 milliwatts of optical power. In any case, purchase an LED with a small beam angle, as much power as possible, and a reasonable speed.

Lenses. Lenses are to the optical world what antennas are the world of RF. The importance of even simple lenses cannot be over emphasized. If any high-frequency RF engineer could build an antenna with 60 dB of gain for less than ten dollars, we would see a lot of happy RF engineers! Since the optical world deals with very small wavelengths, 60 dB (a gain of 1000) is certainly possible.

Although at first it might be hard to believe, the size of the lens on the receiver is very important, but on the transmitter it isn't. That's because at the receiver you are trying to intercept as much light as possible, so the larger the lens, the better. The purpose of the lens at the transmitter is to collimate the beam, so any lens with the right "f" number will work.

OPTICAL AMPLIFIER PARTS LIST

All resistors are ¼-watt, 5%.
R1—100,000 ohms
R2—10,000 ohms
R3, R9, R10, R16, R23—15,000 ohms
R4, R5—150,000 ohms
R6, R17, R24—3300 ohms
R7, R12—100 ohms
R8—3900 ohms
R13, R14—5600 ohms
R11, R15, R18, R21—4700 ohms
R19, R22—22 ohms (see text)
R20—360 ohms
Capacitors
C1, C4, C8—10 µF, 16 volts, electrolytic
C2, C5, C9—0.1 µF, ceramic
C3, C12, C14–C16—0.01 µF, ceramic
C6, C7, C11—470 pF, ceramic, 10%
C10—0.001 µF, ceramic, 10%
C13—100 µF, 16 volts, electrolytic
Semiconductors
Q1—MPS918 NPN transistor (Motorola)
Q2–Q6—2N3904 NPN transistor (Q5 and Q6 must be a matched pair, see text)
D1—PIN diode (Siemens SFH205 940nm usable at 880nm, Panasonic PN323BPA 940 nm, Panasonic PN334PA 880 or 940 nm, see text)
Other components
SPKR1—8- to 45-ohm speaker
Miscellaneous: PC board, wire, solder, etc.

The "speed" of a lens, also called the "f" number, should be familiar to anyone with photography as a hobby. It's a measure of the angle of acceptance of a lens. On the transmitting end, any light from the LED that

TABLE 2—LENS GAIN

Lens Diameter/Area (inch/sq. inch)	Power Gain (at 0.01 sq. inch)	Distance Improvement (85% lens efficiency)
2/3.14	314	×16
3/7.07	707	×24
4/12.6	1260	×33
6/28.3	2830	×49

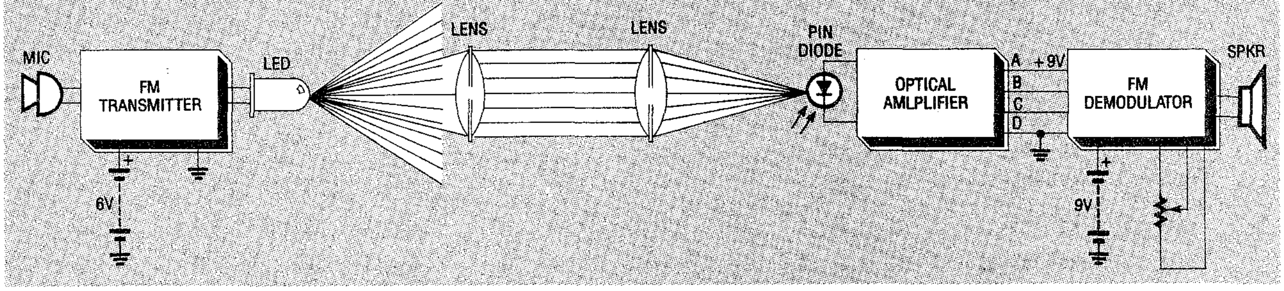

FIG. 4—THE AIR HOP IS BUILT FROM THREE MODULES: an FM transmitter, an optical amplifier, and an FM demodulator.

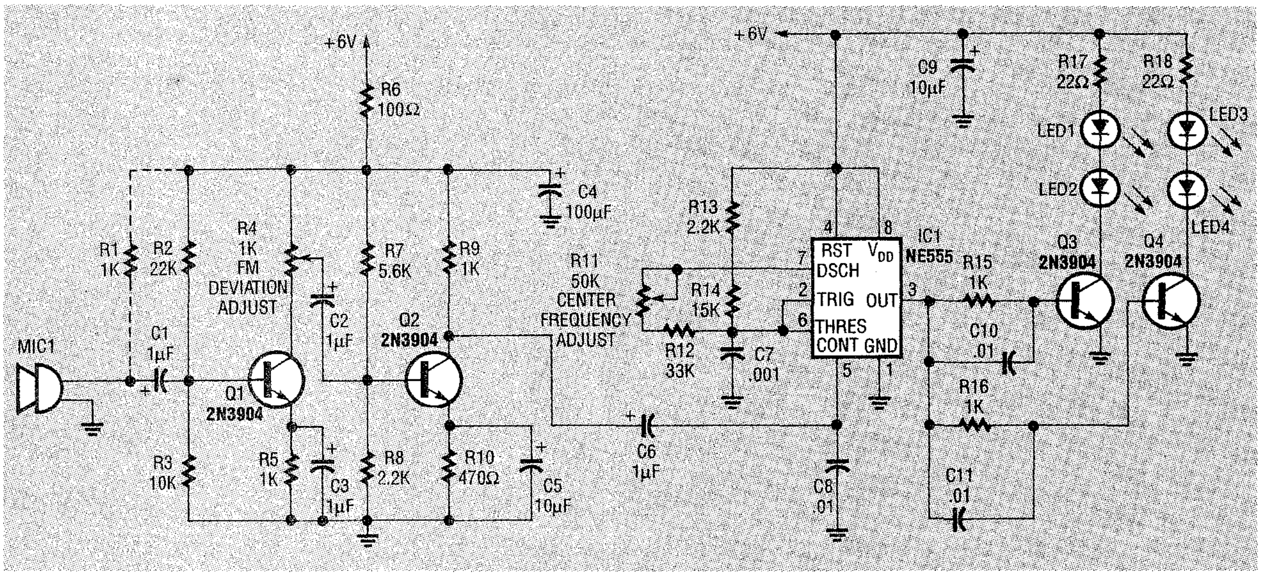

FIG. 5—FM TRANSMITTER MODULE. It provides a microphone amplifier and FM modulator.

FM DEMODULATOR PARTS LIST

All resistors are ¼-watt, 5%.
R1—100 ohms
R2, R3, R6, R11–R13, R16—10,000 ohms
R4, R5—100,000 ohms
R7—33,000 ohms
R8—50,000 ohms, potentiometer
R9, R14, R15—68,000 ohms
R17—4700 ohms
R18—10,000 ohms, potentiometer
R19—22,000 ohms
R20—470,000 ohms
R21—10 ohms

Capacitors
C1, C6, C10, C16—1 µF, 16 volts, electrolytic
C2, C5, C9, C12—0.1 µF, ceramic
C3—100 µF, 16 volts, electrolytic
C4, C7—0.001 µF, ceramic, 10%
C8—470 pF, ceramic, 10%
C11—0.01 µF, ceramic
C13—100 pF, ceramic
C14—4.7 µF, 16 volts, electrolytic
C15—470 µF, 16 volts, electrolytic

Semiconductors
IC1—LM311 or LT1011 comparator
IC2—CD4046 phase locked loop
IC3—MC34119 audio amplifier (Motorola)
Q1—2N3904 NPN transistor

Miscellaneous: 9-volt battery and clip, PC board, blank PC-board material and solder-wick straps for shield (see text), PVC pipe, plastic disks, hardware, wire, solder, etc.

Note: The following items are available from Q-Sat, P.O. Box 110, Boalsburg, PA 16827:

- **Complete Air Hop kit including all three PC boards (does not include speaker, 10K volume control, lenses, PVC pipe and batteries), AIRHOP-KIT—$30.00**
- **Transmitter kit including one IR LED and PC board, AHTX-KIT—$11.00**
- **Transmitter PC board only, AHTX-PCB—$5.00**
- **Optical amplifier kit including PIN diode and PC board, AHOPTAMP-KIT—$12.00**
- **Optical amplifier PC board only, AHOPTAMP-PCB—$6.00**
- **FM demodulator kit including PC board (no speaker or 10K volume control), AHFMDEMOD-KIT—$12.00**
- **FM demodulator PC board only, AHFMDEMOD-PCB—$6.00**

Add $3.00 shipping and handling to all orders. Pennsylvania residents must add 6% sales tax. Please allow 3 to 4 weeks for delivery.

doesn't stay within that cone is lost. A 50-milliwatt LED will be of no value if the light "sprays" out at 90 degrees—any light that can't be coupled into the lens is lost.

The gain of a lens is basically the ratio of the area of the lens to the area of the detector. For example, the area of most PIN diodes is about 0.01 square inch. The area of a 2-inch diameter lens is 3.14 square inches. Therefore, the gain of a 2-inch lens is about 3.14/0.01 or 314. Remember that this amplifier (the lens) consumes no power, has (for our purposes) infinite bandwidth, and adds no noise to the signal. A device of this kind in the electrical world would be nothing short of a miracle.

Table 2 shows the gain for some different size lenses. The calculations assume that no light is absorbed or reflected by the lens, and the detector is at the exact focal point of the lens. Those asumptions are certainly not true. Even fine-quality camera lenses, which are coated with anti-reflective coatings, do not pass 100 percent of the light. There's plenty of room here for experimentation. Some crude experiments showed about 85% of the theoretical gain.

FM transmitter

The Air Hop is built from three modules. The first module is the FM transmitter. Two other modules (the optical amplifier and FM demodulator) comprise the receiver. A block diagram of the system is shown in Fig. 4.

The FM transmitter module, shown in Fig. 5, provides a microphone amplifier (Q1 and Q2) and an FM modulator built from a 555 timer (IC1). There are two adjustments, one for the FM center frequency (R11) and one for the amount of deviation (R4). Resistor R1 is for microphones that require an external power source, such as an electret type. For an external audio source, the input must be limited to a few millivolts.

The output of IC1 (pin 3) is adjusted via R11 so that the frequency is 50 kHz (20 microseconds). The output of the 555 can be frequency modulated by applying the upper trip-point

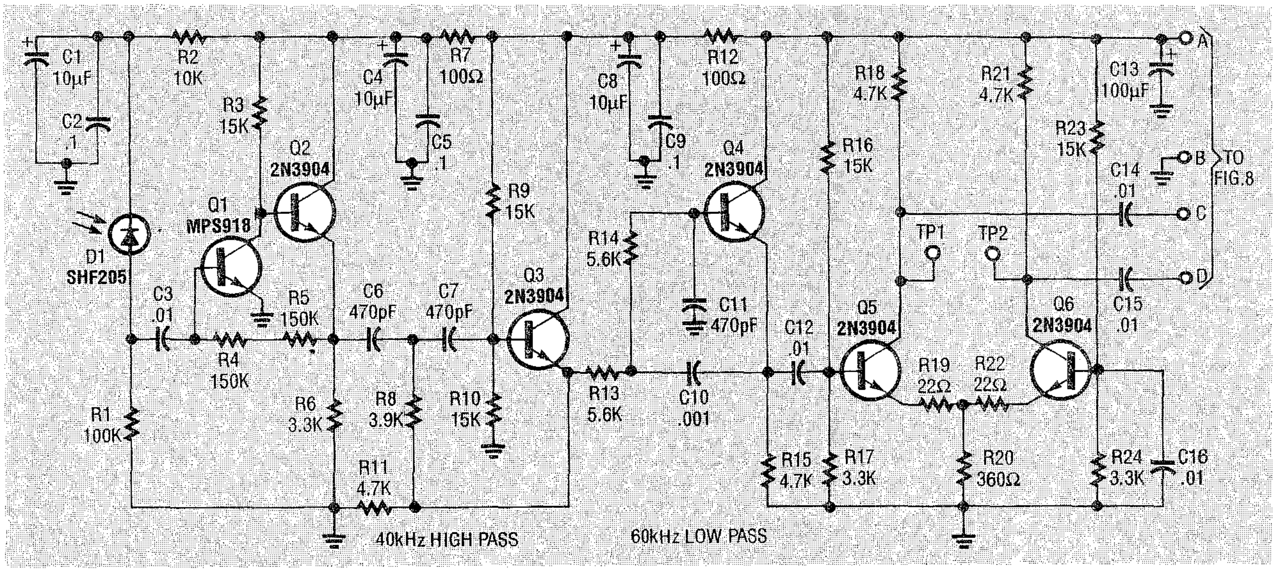

FIG. 6—THE OPTICAL AMPLIFIER MODULE converts the optical signal into an electrical signal, limits its bandwidth, and provides a differential drive to the comparator.

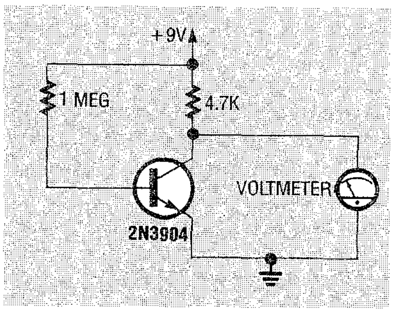

FIG. 7—YOU CAN MATCH transistors Q5 and Q6 using this circuit. Any transistor having less than about a volt between the collector and emitter has too much gain. Choose two transistors that have the closest match between collector-to-emitter voltages.

voltage reference to pin 5. Although you cannot sweep the frequency very far, deviations of 10 percent or so can be obtained easily. The FM deviation is a function of the amplitude of the signal applied to pin 5. If a DC voltage is applied to pin 5 and switched on and off, FSK (digital) data will result. Although the output of the 555 could drive a modest LED, transistor drivers are provided to drive multiple LED's.

Current-limiting resistors R17 and R18 are adjusted to limit the current for your particular LED. Currents of up to 200 milliamps pose no problem for the LED's, but they will drain your batteries quickly. If you're using one LED, values of about 47 ohms will yield about 45 milliamps, average. Systems using two LED's in series will require about 22 ohms for the same current.

The prototype system uses four AA alkaline type batteries for the transmitter power supply. Although they give reasonable life, you may want to use something a little larger, perhaps four D cells.

Optical amplifier

The purpose of the optical amplifier module, shown in Fig. 6, is to convert the optical signal into an electrical signal, limit its bandwidth (to reduce noise), and to provide a differential drive to the comparator.

The PIN diode detector (D1) is AC coupled to a simple transimpedance amplifier consisting of Q1 and Q2. Even though the signal is AC coupled, the bias for the PIN diode must be DC coupled. That is done through resistors R1 and R2. If Air Hop is used in a high ambient light situation, resistor R1 might have to be reduced in value to prevent DC saturation of the PIN diode. If the DC voltage across R1 is greater than about 3 volts in operation, you should lower the value of R1.

The transimpedance resistors (R4 and R5) set the overall gain of the amplifier. Two resistors in series were used instead of just one because every resistor has some capacitance across it. Using two resistors decreases the capacitance by a factor of two. All you have to do is join the two resistors above the PC board.

The output of the transimpedance amplifier is simply its input current times the transimpedance resistance. That's why it's sometimes called a current-to-voltage converter. As you increase the resistance, the signal increases, but the bandwidth decreases. Since the signal increases directly with the value of the resistance and the noise increases with the square root of the resistance, it makes sense to have the resistance as large as possible—it would, if you still had enough bandwidth. That's why Q1 is a VHF transistor.

Since the center frequency of the signal is at 50 kilohertz, it's desirable to limit the bandwidth of the optical amplifier to reduce the total noise. Transistor Q3 and the surrounding components form a two-pole high-pass filter at about 40 kilohertz. That eliminates such low-frequency noise as the 60-hertz optical noise given off by room lights.

Transistor Q4 and its associated circuitry form a 60-kilohertz low-pass filter. That eliminates high-frequency electrical noise such as that from AM radio stations.

When the low-pass and high-pass filters are cascaded, they form a bandpass filter centered

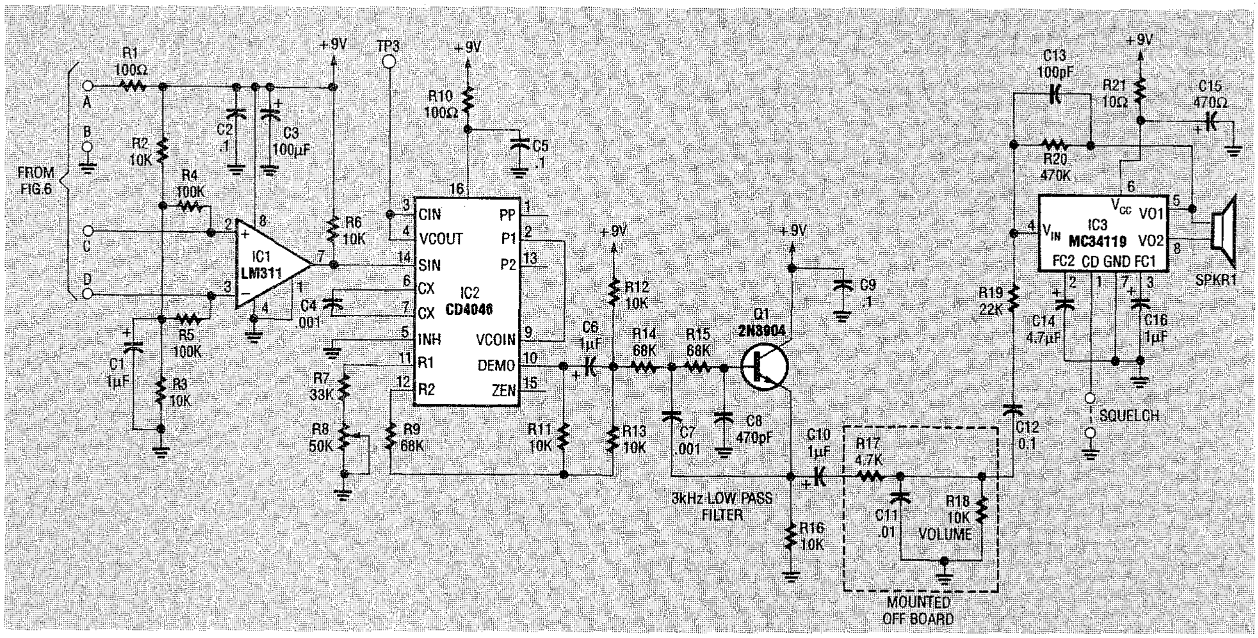

FIG. 8—FM DEMODULATOR. An LM311 comparator converts the small analog signal to a digital level for the CD4046 phase-locked loop, which is configured as a first-order FM demodulator.

on 50 kilohertz, with a pass band of about 20 kilohertz. You could reduce the noise by making the filter narrower, or by putting a narrower filter between the output of the optical amplifier and the input of the demodulation board. The disadvantage of doing that is that you would have to make the narrow filter tunable, and use a scope to adjust it.

Transistors Q5 and Q6 form a differential amplifier that is the only real gain stage in the optical amplifier besides Q1. The purpose of using a differential amplifier is so that a differential signal will be available to drive the voltage comparator. It's nice to drive a comparator differentially because you get twice the signal but not twice the noise. There is one problem with a differential amplifier: if you want a reasonable amount of gain, the transistors must be well matched. That prevents one transistor from "current hogging" and saturating.

The matching of transistors can be done a number of different ways—a curve tracer is best but most people don't have access to one. Next best is a meter that actually measures gain at a given base or collector current. As a last resort, the circuit in Fig. 7 can be used. Some kind of socket, such as an IC socket with only three pins can be used to hold the transistor. Simply measure the voltage from the collector to emitter, and choose two transistors that have the closest match between the collector-to-emitter voltage. Any transistor having less than about a volt has too much gain.

It's also a good idea to use bias resistors that have nearly the same values. Try to match the values of R16 and R23 and R17 and R24 as close as possible. If the final amplifier isn't matched within a volt, you might want to adjust the values of R19 and R22. Those resistors were purposely put there to allow some "balancing" of the differential amplifier. Values from 10 to 33 ohms should be fine. (Potentiometers were not used because they are expensive.)

FM demodulator

The schematic for the FM demodulator is shown in Fig. 8. An LM311 comparator (IC1) converts the rather small analog signal to a digital level for the CD4046 phase-locked loop (IC2). Remember that the amplitude of the recovered audio has nothing to do with the amplitude of the received signal. The amplitude of the recovered audio depends only on the amount of frequency deviation set by the transmitter and the amplitude of your voice.

The phase-locked loop (IC2) is configured as a first-order FM demodulator. With no input signal, the center frequency of the loop (pin 3 of IC2, which is also TP3) is adjusted by R8 for a frequency of 50 kilohertz. Because the variation from one CD4046 to another can be quite large, you might have to adjust R7 and, perhaps, R9 as well.

The demodulated output from IC2 is low-pass filtered at 3 kilohertz by Q1 and its associated circuitry, and then sent to audio power amplifier IC3, a Motorola MC34119. A wider bandwidth can be obtained by making the filter higher in frequency. Since the "carrier" frequency is only 50 kilohertz, don't try extending the audio bandwidth to more than 6 or 7 kilohertz. Pin 1 of the MC34119 can be used for squelch or in conjunction with a push-to-talk switch to silence the receiver while transmitting. If you don't need the squelch, simply jumper pin 1 of IC3 to ground.

Although you can use a standard alkaline 9-volt battery to power the receiver, the current draw can be quite high on voice peaks. Six AA cells would be a much better choice.

We'll finish up the project next month with complete construction details. **R-E**