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FIBER OPTICS IN AMATEUR RADIO

Waveguide of the future

Every generation of amateur radio pioneers has its frontier. In Maxim's day, it was those valueless short wavelengths below 200 meters. By mid-century, the challenge was to master the "very highs," and a generation ago a few hardy hams, armed with tin snips, hacksaws, and blowtorches, set out to populate the microwave spectrum. Tomorrow's frontier is optical communications, and this article will tell you how to go about becoming a pioneer. We'll start by reviewing the electromagnetic spectrum, and follow this with a brief discussion of guided electromagnetic waves. Next, we'll look at how optical fiber functions as a transmission line, and contemplate the propagation of light in free space. We'll then identify sources of optical communications components and equipment. Finally, we'll conclude with a look into the optical hamshack of the future.

Time, speed, and distance

Since the 1880s, when Hertz first harnessed them in the laboratory, the substance of ham radio communications has been electromagnetic waves. These orthogonal combinations of electric and magnetic fields, propagating through free space at the fastest velocity known to nature, can be modulated; that is, they can be changed from one cycle to the next, to convey incredible amounts of information. This is what communication is all about.

The behavior of electromagnetic waves is anything but arbitrary, and was contemplated extensively by Maxwell in the 1860s. He applied vector calculus to the derivation of four equations[1] that formed the basis for Hertz' experiments. Maxwell's equations allow us to quantify the concepts of frequency and wavelength, characteristic impedance and the speed of light. At a more fundamental level, Maxwell tells us that all electromagnetic waves, whether emanating from sunlight, satellite, or searchlight, behave fundamentally alike and follow the same rules of the universe.

One of those rules involves the relationship between frequency and wavelength—the two benchmarks by which we subdivide the electromagnetic spectrum. Generations of engineers have memorized a simple formula or two, but we hams want to understand the why behind what we do. So let's derive the frequency-wavelength relationship by taking a trip in the family car.

I currently reside in Williamsport, in rural Central Pennsylvania (Grid Square FN11). That's about 200 miles from Manhattan, 200 miles from Pittsburgh, 200 miles from Philadelphia, 200 miles from Baltimore, 200 miles from Washington. . . 200 miles from anywhere! If I set out to drive to any of these population centers, and average 50 miles per hour, its going to take me four hours to get there.

The math used to derive the driving time is so deceptively simple, that it's easy to miss the elegance of the underlying algebra. In physics and the family car, the relationship between distance, speed, and time is simply:

$$d = v * t \qquad (1)$$

and if we know any two of the related quantities, we know the third. Well, the same equation holds for any electromagnetic wave travel-

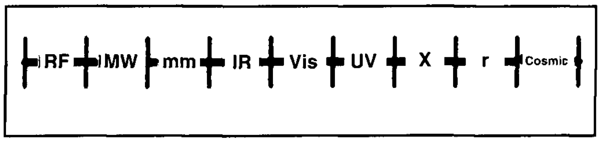

Figure 1. The electromagnetic spectrum.

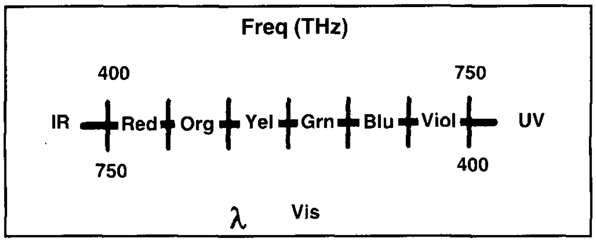

Figure 2. The visible spectrum.

ing through any medium, but if we consider one special medium (free space) the equation becomes:

$$d = c * t \tag{2}$$

where c stands for a very specific velocity, the speed of light in free space, or 300 million meters per second (a constant of nature).

It happens that the distance occupied by one cycle of an electromagnetic wave is its wavelength, abbreviated λ. Substituting wavelength for distance, we get:

$$\lambda = c * t \tag{3}$$

where t now represents the period of the wave—the time it takes for one cycle to pass a given point. Since period is measured in seconds per cycle, and frequency in cycles per second, it's easy to see that the two must be reciprocals of each other. Consequently:

$$\lambda = c * 1/f \tag{4}$$

which can in turn be rewritten as:

$$c = \lambda * f \tag{5}$$

which is not only the textbook equation that we all know and love so well, but will lead us to a full understanding of the electromagnetic spectrum. In the time it takes me to drive to Manhattan. Or Baltimore. Or Pittsburgh. Or...

DC to daylight, and beyond

Let's take a look at an electromagnetic continuum (**Figure 1**). The spectrum is variously divided into a number of segments, including audio frequencies, radio frequencies, microwaves, millimeter-waves, infrared, visible, and ultraviolet light, X-rays, Gamma rays, and cosmic rays. It's important to remember that these are all electromagnetic waves following Maxwell's equations, obeying the same rules of nature, differing only by their frequency (and hence corresponding wavelength). In other words, each segment of the continuum is still light, albeit of a different color.

Yesterday's radio amateur concentrated on harnessing light in the RF spectrum. Today, many hams are working at microwave, and more than a few in the millimeter-waves. The province of the optical communicator is the infrared and visible spectra. What we'll choose to modulate tomorrow is anybody's guess.

Let's zoom in on the visible rainbow specifically, as seen in **Figure 2**. Here we relate color to its frequency and wavelength, remembering (in accordance with **Equation 5**) that the speed of light is a constant; that is, if one goes up, the other will go down. If we choose to measure frequency in TeraHertz* and wavelength in nanometers, an interesting coincidence asserts itself: the numeric frequencies defining the visible spectrum are equal to the numeric wavelengths of the opposite band ends. Even more startling is the discovery that the center of visible light (found by taking the square root of the product of two endpoints) has a frequency of 547.7 THz, and a wavelength of 547.7 nm! However, the best coincidence of all is that it is this central wavelength/frequency that corresponds to the peak spectral response of our sunlight-adapted eyes. Thus, it appears that both our eyes and our sun have evolved in accordance with Maxwell's equations.

Fiber optic communications take place primarily in the visible and near-infrared spectra. **Table 1** shows the center frequencies and wavelengths of the three most widely used infrared "bands." If you are to be a pioneer in this communications mode, you'll need to begin thinking in terms of frequencies in the hundreds of TeraHertz, and wavelengths on the order hundreds of nanometers. It's not so different from the transition made by microwavers a few year ago, into thinking in terms of frequency in GigaHertz,** and wavelength in centimeters. Higher frequencies, shorter wavelengths has always been the name of the game.

Optical: Why bother?

In an excellent previous article, Mike Gruchalla[2] characterized the chief advantage of fiber optic communications links in terms of their impressive information capacity. Let's define electronic communication as transferring

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*Tera, for 10^{12}, comes to us from the Greek Teras, or Monster.

**Giga, for 10^{9}, derives from the Greek Gigas, or Giant.

information from Point A to Point B via electronic means. That generally means modulating an electromagnetic wave (carrier) in some way. Whether the carrier is present or suppressed, the modulation process always generates sidebands, which define a signal bandwidth. As a rule, the greater the information content per unit time, the greater that bandwidth. This principle is the basic tenet of information theory.[3] It's also the reason why optical carriers offer an advantage over their RF or microwave counterparts.

820	1300	1550	nm
366	231	193	THz

Table 1. Common IR fiber frequencies.

Application	fc	BW	%	Q
AM radio	1 MHz	10 kHz	1	100
UHF TV	600 MHz	6 MHz	1	100
TVRO	4 GHz	40 MHz	1	100
IR fiber	350 THz	3.5 THz	1	100

Table 2. A few familiar applications that show what's readily achievable as a realizable system Q.

Whatever the bandwidth of a modulated signal, the equipment at both ends of the communications link must be able to pass it. Otherwise, we begin to lose sidebands, which after all contain the information we wish to convey. Thus, we're concerned with the bandwidth of our transmit and receive circuits, antennas, and transmission media. For any frequency-selective circuit, bandwidth and carrier frequency are related by Q:

$$Q = f_C / BW \tag{6}$$

so that, for a given circuit Q, the higher the signal carrier frequency, the wider its bandwidth (and the more information it can carry). What exactly do we mean by "for a given circuit Q?" Simply this: for any application, there is a minimum practical circuit Q that can be readily achieved in practice. Any lower Q in transmit amplifiers, and gain goes down unacceptably. Any lower Q in receiver front ends, and intermodulation distortion and image interference become a problem. Any lower Q in antennas, and their radiation pattern degrades excessively. Consequently, for any application, we are limited in bandwidth by realizable system Q.

Just what is a realizable system Q? Let's take a look at a few familiar applications (**Table 2**) to see what's readily achievable. Consider first an AM radio station transmitting in the vicinity of 1 MHz. The maximum modulating frequency is 5 kHz, and we're using double-sideband AM. This means we have an upper sideband extending out to 5 kHz above the carrier, and a lower sideband extending a like distance below it, for a total signal bandwidth of 10 kHz. Dividing carrier frequency by bandwidth, we see that AM radio uses a system Q of around 100.

Next, lets consider UHF television. Take, for example, TV channel 35, more or less in the middle of the dial (at least since Channels 70 through 83 were reallocated by the FCC to cellular telephone). The assigned channel extends from 596 to 602 MHz, which gives us a center frequency of 599 MHz, a channel bandwidth of 6 MHz, and a Q of around 100.

How about C-band satellite TV? These wideband FM downlinks are transmitted at a carrier frequency in the 3.7 to 4.2 GHz band, with 40 MHz of bandwidth per channel, for a system Q of around 100!

Do you begin to see a pattern here? Of course, there are counterexamples abundant, but they do not negate the fact that, in a number of communications applications, system Q of around 100 (that is, modulation bandwidths on the order of one percent of carrier frequency) are common. Now if this trend holds through optical frequencies (and we have no reason to expect it shouldn't), we should also expect bandwidths on the order of one percent of carrier frequency. These are incredibly high carrier frequencies we're talking about! Which implies mind-boggling bandwidths, and correspondingly immense information capacity. Which is the primary advantage of optical communications.

Let's consider an optical communications system using the rather common infrared carrier wavelength of 850 nm. This corresponds to a frequency on the order of 350 THz. Using our "one percent rule," we would expect an information bandwidth on the order of . . . 3.5 THz! That's 3,500,000 MHz—about 100 times as much spectrum as all United States ham radio allocations, HF through millimeter waves, put together! In terms of the applications cited above, we're talking enough spectrum to support 87,000 satellite TV channels, or 583,000 standard NTSC TV channels, or about 350 million simultaneous AM voice signals (see **Table 3**)! Now, even if our bandwidth estimate is optimistic by even so much as a couple of orders of magnitude, it's still apparent that optical communications afford us with an incredible information capacity.

Keep it in the pipe

This section is a great time saver. If you're interested in just how optical fibers function, you can either read a mathematical optics textbook, and be totally confused, or read this sec-

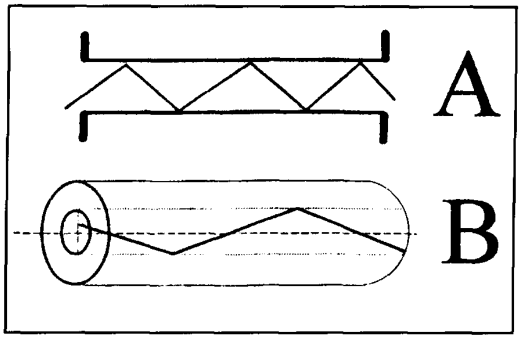

Figure 3. (A) How microwave signals propagate through rectangular waveguide. (B) Light propagation in a fiber.

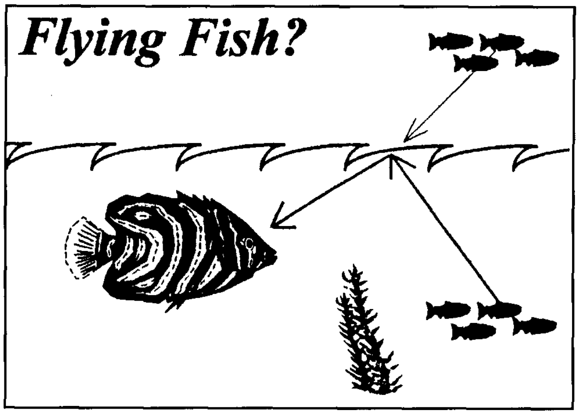

Figure 4. The phenomenon of total internal reflection.

tion. . . and be just as confused! (If you wish to avoid confusion altogether, feel free to skip this section. I don't mind.)

Optical fiber, like coax cable or rectangular waveguide, is a low-loss transmission medium for electromagnetic waves. You've probably seen how microwave signals propagate through rectangular waveguide (**Figure 3A**). Because waveguide has conductive, metallic walls, it's easy to see how the signals can bounce off the walls of the guide, to achieve forward propagation.[4] The model most often used to represent light propagation in a fiber (**Figure 3B**) shows signal reflection, too, but that's misleading. After all, how can light bounce off the edge of a transparent glass or plastic pipe?

It can't, of course. The trick for keeping light in the pipe is that the optical fiber is really a concentric sandwich of two different materials. The inner glass or plastic portion (called the *core*) is surrounded by a thin *cladding* of a slightly different type of glass or plastic, which is slightly less dense (optically) than the core. If light were propagating in the cladding, it would then be moving faster than light traveling in the core. It is the difference in propagation *speeds* that enables the light applied to a fiber to stay within the core and travel forward. . . at slightly less than what we call the *speed of light*.

To understand the operation of optical fibers, we'll invoke the *law of refraction*. When light traveling in a given medium (at a given speed) enters another medium (in which light travels at a different speed), the light ray bends. If bent enough, the light rays will re-enter the original medium, a phenomenon called *total internal reflection*. Consider, for example, Charlie Piranha (see **Figure 4**) out searching for a snack. Now who do we see cringing behind a clump of kelp but the School Lunch Program. You'd think they're safely out of sight, but guess again. As Charlie looks up, he sees the Catch of the Day reflected in the interface between water and air. Now Charlie's not one to be fooled by the Flying Fish optical illusion. He knows (and now, so do you) how sufficient refraction can result in total internal reflection.

The *angle of refraction*, the degree to which light is bent can be predicted mathematically, as a function of the relative optical density of the two materials in question. By proper design of cladding and core, we can use the law of refraction to achieve total internal reflection in the cable. That is, we can bend any light entering the cladding, forcing it to re-enter and stay within the core. Here's how that works.

Remember the **c** we introduced in **Equation 2**—the forward propagation velocity of radiant electromagnetic energy in free space? In any other material (such as glass or plastic), light will move more slowly. We can define *relative* propagation velocity, or *velocity factor*, as the speed of light in a given material relative to that in a vacuum. Mathematically:

$$V_r = V_x/C \qquad (7)$$

where $\mathbf{V_r}$ is velocity factor (or relative velocity), $\mathbf{V_x}$ is the propagation velocity in our material of interest, and **c** is 3×10^8 meters per second—the speed of light in a vacuum.

We can create an optical fiber by surrounding a core (of transparent material **1**) with a cladding (made of transparent material **2**) as seen in **Figure 5**. To transmit light, the propagation velocity in the cladding must be greater than in the core, or:

$$V_r(2) > V_r(1) \qquad \mathbf{(8)}$$

Another way to indirectly describe propagation velocity in material **x** is to refer to the material's *index of refraction*, abbreviated $\mathbf{n_x}$. Index of refraction is the reciprocal of relative velocity, or:

$$n_x = 1 / V_x \qquad \mathbf{(9)}$$

Combining **Equations 9** and **8**, we see that:

$$n_1 > n_2 \qquad (10)$$

A defining characteristic of optical fibers is Numeric Aperture, **NA**, a ratio based upon these two indices of refraction:

$$NA = [n_1^2 - n_2^2]^{1/2} \qquad (11)$$

The *Law of Refraction*, also known as *Snell's Law*, quantifies the degree of bending that occurs when light travels between two media of different refractive indices. All angles are measured with respect to the normal (a line perpendicular to the plane of the interface of the two materials).

$$n_1 \text{ Sin } \Theta_1 = n_2 \text{ Sin } \Theta_2 \qquad (12)$$

We can now solve Snell's Law for the special case of total internal reflection, finding the *critical angle*, Φ_c, at which light will propagate through a fiber:

$$\Phi_c = \text{Cos}^{-1} (n_2 / n_1) \qquad (13)$$

Finally, if we combine **Equations 11** and **13**, we derive the acceptance cone; that is, the angle below which light must be *launched* into the end of an optical fiber, in order for it to propagate:

$$\Theta_{accept} = 2 \text{ Sin}^{-1} (NA) \qquad (14)$$

These equations allow us to calculate the critical operating parameters of optical fiber. Now let's look at what optical fiber's good for, and how to use it.

Waveguide of the future

As I mentioned previously, optical fiber can be constructed from either plastic or glass. In either case, it's necessary to surround a core of material $\mathbf{n_1}$ with a cladding of *lower* refractive index $\mathbf{n_2}$. I suppose it's possible to combine a glass core with plastic cladding or vice-versa, but in actual practice it's all one or the other. Glass fibers have extremely low loss (a dB or less per kilometer), and are suitable for GigaBaud data rates over great distances. Unfortunately, glass fiber will cost you anywhere from dollars to tens of dollars per foot, on a par with the best Heliax™ microwave cables. Plastic fiber, on the other hand, is cheap (pennies to dimes per foot), somewhat lossy (a good fraction of a dB per meter), and is used at kiloBaud data rates over limited distances. Think of it as the RG-58 of the optical world, in terms of both performance and cost. While glass fiber shines in long-haul trunkline applications, it's plastic fiber with which you're most likely to wire your home or hamshack.

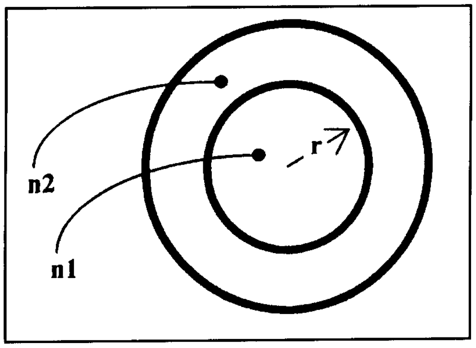

Figure 5. Creation of an optical fiber by surrounding a core with a cladding.

87 k	TVRO channels
583 k	NTSC TV channels
350 M	Voice channels

Table 3. Channels supported by 3.5 THz bandwidth.

At microwave frequencies, we normally operate rectangular waveguide in a single dominant *mode*, as seen in **Figure 3A**. This means only a single ray propagates through the guide, and it always reaches the walls of the guide at a fixed angle. Thus, in the absence of reflective losses, all signals exiting the waveguide will do so *in phase*, and there will be no cancellation of propagated energy. Because single-mode propagation in waveguide only occurs when the physical aperture of the guide is on the order of a half wavelength, a given guide will exhibit only a limited operating bandwidth. For example, WR-90 X-band waveguide operates in its primary mode over a frequency range of only 8 to 12 GHz.

It's possible to achieve single-mode propagation in optical fiber as well; in fact, this would lead to the lowest possible signal attenuation. However, if that half-wavelength guideline holds here as well, we would need a core radius (**r** in **Figure 5**) on the order of a fraction of a micron.* Multi-mode fibers are more practical in that the physical dimensions are more realizable, although with light rays entering and exiting the fiber at various angles, you can see that some of the waves are going to emerge *out of phase*, and cancel. It is this phase cancellation that accounts for much of the loss in multimode fibers.

Certainly the simplest way for hams to apply fiber-optic techniques would be to obtain plastic multi-mode fiber with a fairly wide acceptance cone, and a fairly large core radius, and epoxy the polished ends of such fiber directly to LEDs (used as modulated optical transmitters) and phototransistors (used as optical demodulators). This is, in fact, the approach used in the optical projects proposed at the end of this article, although many of the plastic fiber kits referenced do use connectors between the fiber and the optoelectronic active devices.

Free-space lightwave communications

Hams have been doing a lot of work with free-space laser communications in recent years, and this DX mode has a great deal in common with fiber optic communication. In both cases, it's necessary to modulate a light source, either visible or infrared, with either analog or digital information. Because both free-space and guided light communications use LEDs or lasers as signal sources, the electronic portion of the transmit equipment will likely be identical. Also, the receive circuitry for free-space optical communications will have a great deal in common with guided optical applications. Thus we have an opportunity for some interesting synergy.

Consider, for example, the current** laser DX record shot of 157.7 miles reported in **Reference 5**. KY7B and WA7LYI used 15 mW HeCd lasers as sources, and photo-multiplier tubes in their receivers. A number of experimental long-haul fiber optic links have used similar equipment. At a more modest level, the HeNe laser communications systems used by NU1N[6,7] use transmit and receive electronics identical to those commonly encountered in the fiber optic industry. And WA2NDM's laser diode driving circuit[8] is ideally suited to either free-space or fiber applications.

In the following section, we'll be looking at some parts kits for fiber optic projects. Be aware that, at least for short-haul paths, they may prove suitable for free-space experiments as well. Working your own grid square with visible light may well be a goal to set your sights on!

Piecepart potpourri

When I first started microwaving some 25 or so years ago, my biggest challenge was locating sources of components. Short of stripping out surplus military equipment (which was, thankfully, abundant), there was little to be found in the way of affordable microwave parts. Today's optical experimenter is more fortunate. Because the much touted Information Superhighway is to be paved with glass, educational institutions are anxious to incorporate fiber into their curricula. Numerous commercial vendors are eager to supply them with parts and kits which, it just so happens, will meet the ham experimenter's needs perfectly. The **Appendix** lists a few such vendors and their wares.

For amateur applications, the best optical transmission line is probably Super-ESKA SH4001. This inexpensive multi-mode plastic fiber, 900 microns in diameter, is optimized for use with red visible light (such as that which emanates from inexpensive LEDs). Its numerical aperture is 0.5, for an acceptance cone of 60 degrees. Expect insertion loss to be on the order of 0.3 dB per meter. The protective buffer covering ESKA can be stripped off with ordinary AWG 20 wire strippers (although no-nick strippers are better to avoid damaging the cladding). This fiber can be cut with diagonal cutters (although a hot-knife cut generally requires no polishing), and its ends polished, when necessary, with 400 to 600 grit wet-or-dry emery cloth. In short, ESKA users can expect low cost ($1 per meter in small quantities, *much* less in bulk), moderate performance, and ease of use.

For interconnect, I favor the AMP Optimate DNP (stands for dry, non-polish) line of optical connectors. Plugs, bulkhead receptacles, and active device mounts all cost about $1 each in singles, less in quantity. These plastic connectors require no specialized tools, and are a perfect for ESKA fiber. Most of the kits listed in the **Appendix** use DNP connectors; the rest use equally inexpensive Motorola plastic SMAs, which are dimensionally similar to the familiar SMA microwave connector.

For light sources, red T 1-3/4 size LEDs work great. They fit the AMP DNP device mounts if you file off the curved lens and polish the end with fine grit emery cloth. For sensitive detectors, look for some inexpensive phototransistors. For faster frequency response (high Baud rates), you might prefer a photodiode. Here's a tip: when forward biased, LEDs emit photons. When reverse biased, they make dandy photo diodes. It's hard to beat Radio Shack variety for a low-cost "matched pair."

A look at the optical hamshack

Amateur radio has traditionally been as much an analog discipline as pre-CD musical recording (if you'll pardon the analogy). However, much like the digitization of music, I suppose it was inevitable that the computer

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*Actually, by making Numeric Aperture very small, it's possible to raise the required radius for single-mode operation to several microns. But that's still inconveniently (and expensively) small. Single-mode optical fibers are the most costly, and least lossy, available.

**As of this writing (August 1994). Since records are made to be broken, a new one may be in place by the time you read this.

would in time invade our hamshacks. Today, microprocessors have insinuated themselves into our transceivers, teletypes, antenna rotators, signal processors, satellite trackers, Morse code keys, and even our logbooks! It is the increasing digitization of amateur radio which will likely provide our window into the realm of optical communications.

If you've ever tried to copy weak signals with a computer on in the shack, you've probably already noticed what I call the *aviary effect*: more birdies than Palmer ever hit. Computers, for all their utility, are horrendous sources of RFI. Shield them though we might, the interference persists. And even if you remote the computer, the cables which interconnect it to your rig, no matter how well shielded, will still spew out garbage.

Let's exile the hamshack computer to the basement, and access it remotely with *optical fiber*. After all, fiber is more secure than the best shielded coax. An inexpensive fiber optic duplex digital link will do the trick (they're available in kit form). While we're at it, let's digitize our rotor signals, and send them up the tower on plastic, rather than copper. As for driving our radios, the TNC, DSP box, etc., interface whatever is possible optically for the greatest possible interference immunity.

Ever run a phone patch through a local repeater? You'll remember that it was relatively easy to interface, because the frequency response of your telephone line is only about 3 kHz. How about a VideoPhone patch through an ATV repeater? A bit more of a challenge to pipe around 6 MHz wide video isn't it? This sounds like a job for...SuperFiber! And if we digitize the video first (standards are now emerging for digital HDTV), we can employ digital compression techniques to either increase our resolution at a given Baud rate, or reduce the Baud rate for our original resolution. There's every reason to expect fiber optic hams to emerge at the forefront of video teleconferencing technology.

We've only scratched the surface in this article. Optical fiber is ideally suited to piping high data rate digital signals around the shack, without the problems of RFI which wire systems suffer. Anything that can be thought can be digitized, and anything that can be digitized can be transmitted optically. The possibilities are without limit.

Conclusion

In years past, amateur radio innovation opened up new vistas for the electronic communications industry. We hams have pioneered the use of every major segment of the spectrum, and have paved the way for worldwide digital, microwave, and satellite distribution of information. For once, we seem to be taking a back seat to the laboratories of industry and the halls of academia; the fiber optic revolution has nearly passed us by. That commercial exploitation of optical communications has preceded, rather than following, amateur use is a function more of interest than of aptitude. To hams, fiber optics can be seen as a solution in search of a problem. As we begin to identify applications that can only be satisfied by wide-band optical links, we'll enjoy an opportunity to return to our accustomed role in technological development: as innovators of the highest order.

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Appendix: Sources of Components and Supplies

1. Digi-Key Corp., P.O. Box 677, Thief River Falls, Minnesota 56701, (800) 344-4539. Fiber optics educations kits, ESKA plastic optical fiber, AMP DNP connectors, plastic fiber tool kit.
2. Mouser Electronics, 2401 Hwy 287 N, Mansfield, Texas 76063, (800) 346-6873. Fiber optics educational kits, visible and infrared phototransistors and LEDs, plastic fiber tool kit.
3. MWK Industries, 198 Lewis Court, Corona, California 91720, (800) 356-7714. Diode and HeNe lasers, glass optical fiber (with and without connectors), fiber optics educational kits.
4. Industrial Fiber Optics, P.O. Box 3576, Scottsdale, Arizona 85271. Manufacturer of fiber optics educational kits, lab manual (distributed through MWK, Digi-key, and Mouser, above).
5. Fiber Sciences, P.O. Box 5355, Chatsworth, California 91313. Fiber optic voice transmitter/receiver kit.
6. Jameco Electronic Components, 1355 Shoreway Road, Belmont, California 94002, (800) 831-4242. Visible LEDs in a variety of colors, opto-isolators.