The future of fiber communications: solitons in an all-optical system

By Linn F. Mollenauer

In an "all optical" fiber system—one without electronic repeaters—a single fiber could transmit as much as 100 Gbit/sec over thousands of kilometers. Such performance would be obtained by using optical gain to overcome fiber loss and by transmitting the signals as nonspreading, soliton pulses.

Because of their ability to handle large amounts of information at low cost, optical fibers are rapidly taking over in telecommunications. Signals race up and down the Boston-New York-Washington corridor on bundles of fibers, with each fiber carrying hundreds of megabits per second, and the network is now being extended across the midwest and on to California. A 3400-km long, 400-Mbit/sec system links major Japanese cities. The first transatlantic fiber cable, from Tuckerton, N.J., to Widemouth, England, and Pennmarch, France, is scheduled to begin service in 1988. A transpacific cable is soon to follow. These developments are especially remarkable, given that the first low loss (<1 dB/km) fibers were produced little over a decade ago.

As marvelous as the present systems are, however, they still use but a tiny fraction of the potential information carrying capacity of optical fibers. That is, in a conventional system, the optical signals are detected and electronically regenerated every 20 to 100 km before continuing along the next span of fiber. But electronic repeaters limit rates to ~1 Gbit/sec or less per channel. Furthermore, the use of multiple channels, or wavelength multiplexing, is difficult and cumbersome, as the demultiplexing/multiplexing must be performed at each repeater. Thus, the only sensible way to achieve higher bit rates is by allowing the signals to remain strictly optical in nature.

Clearly, one necessary ingredient of such an all optical system is gain to overcome the fiber losses. Lumped amplifiers have been suggested, but there is a better way—that is, to make the fiber itself a distributed amplifier, through use of the stimulated Raman effect. In particular, silica glass fibers exhibit a broad Raman gain band, peaking at a frequency about 450 cm^{-1} lower than that of the pump. Figure 1 shows a system based on such Raman gain, where cw pump power is injected at every distance L (the "amplification period") along the fiber, by means of directional couplers. The wavelength-dependent couplers provide for efficient injection of the pump power, but allow the sig-

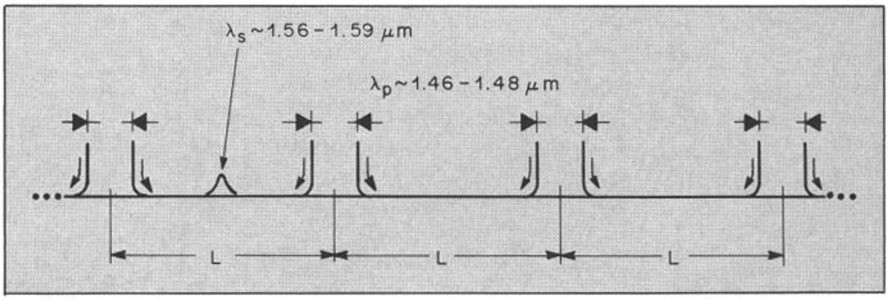

FIGURE 1. Segment of all-optical soliton-based system. Single laser diodes are shown here at each coupler, but the required pump power, ~50 to 100 mW, would best be supplied by a battery of, say, a dozen lasers, each tuned to a slightly different wavelength, their outputs combined through a diffraction grating. In this way, stimulated Brillouin back scattering can be avoided. The multiplicity of pump lasers would also provide a built-in, fail-safe redundancy.

nal pulses to continue down the main fiber with little loss. A system may contain as many as 100 or more amplification periods.

In the system of Fig. 1, loss at the pump wavelength makes the Raman gain nonuniform within each amplification period. Nevertheless, the signal pulse energy fluctuations can be surprisingly small. Figure 2 shows gain and signal energy for L = 40 km and low-loss single-mode fiber. (The loss figures assumed there are now routinely attained in production fibers.) The result of bidirectional pumping, the Raman gain is the sum of two decaying exponentials and is adjusted (through control of the pump intensity) such that there is no net signal gain or loss over the period. (That is, the integral over the period of the net gain/loss coefficient α_{eff} is zero.) Note that with the Raman gain, the signal pulse energy varies by no more than about ±8%, whereas without it, more than 80% of the signal energy would be lost in just one period.

Of equal importance to the need to overcome fiber loss is the need to counteract the tendency of the fiber's dispersion to broaden pulses. Solitons are the solution to that problem.[1] Briefly stated, the soliton is a pulse of the proper shape (*sech*^{2} intensity envelope) and critical peak power, such that effects of index nonlinearity exactly cancel dispersive broadening (see box).

Nevertheless, despite the existence of a "critical" power for the soliton, there is nothing critical about its creation: if the pulse shape or power are at first not quite right, the pulse will simply reshape itself until it becomes a soliton. Thus, within a certain wide range of peak intensities, soliton formation is not to be avoided. The existence of fiber solitons and their stable transmission over many kilometers has been well verified experimentally.[2,3]

A question of prime importance here is just how well the solitons (normally considered to be of con-

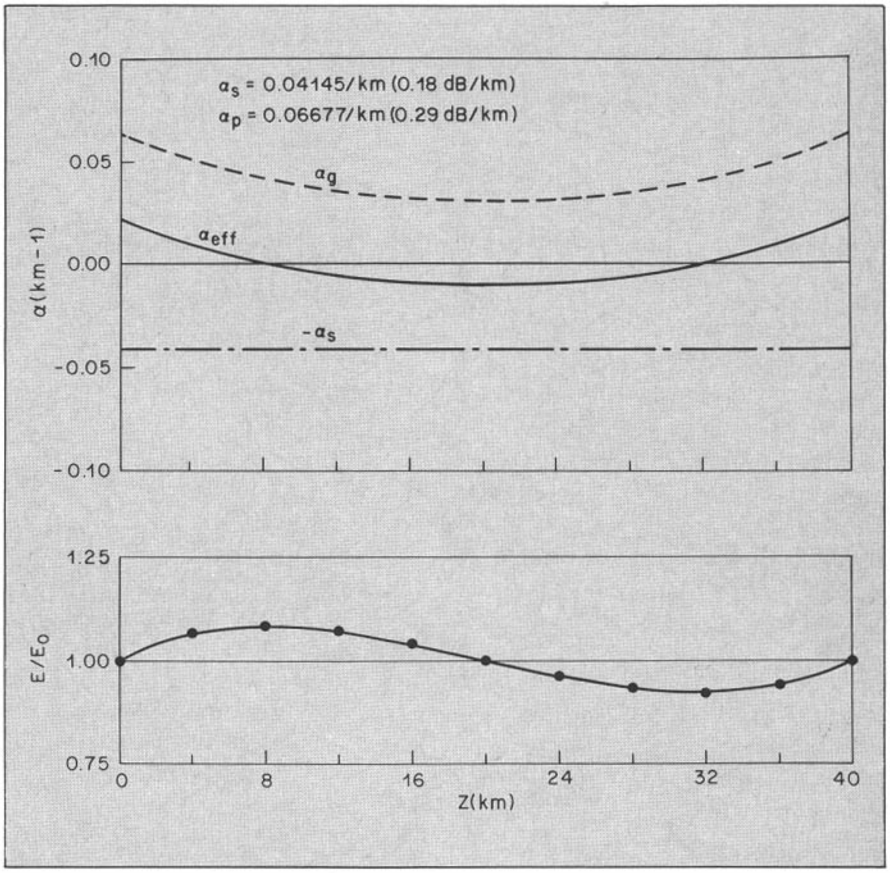

FIGURE 2. (a) Coefficients of loss ($-\alpha_s$) and Raman gain (α_g) and their algebraic sum (α_{eff}) for an amplification period L = 40 km. (b) The corresponding normalized pulse energy.

Fiber nonlinearity and solitons

The fiber is nonlinear, that is, its index can be written as

$$n = n_0 + n_2 I, \tag{1}$$

where I is the intensity in W/cm^2 and $n_2 = 3.2 \times 10^{-16}$ cm^2/W for quartz glass. When effects of the nonlinearity are included, pulse propagation in the fiber is governed by the nonlinear Schrödinger equation:

$$-i\frac{\partial u}{\partial \xi} = \frac{1}{2}\frac{\partial^2 u}{\partial s^2} + |u|^2 u - i\Gamma u, \tag{2}$$

where all quantities are in dimensionless form. In particular, u is the pulse envelope function, ξ is z measured in units of $2z_0/\pi$ (see Eq. 4), s is time as perceived by an observer moving with the pulse, measured in units related to the pulse width, and Γ corresponds to α_{eff} times z_0/π. In Eq. 2, the first term on the right describes the effects of dispersion, while the second is derived from the index nonlinearity.

For a fiber with negligible gain or loss ($\Gamma \cong 0$), the soliton is the special solution

$$u(\xi, s) = sech(s)e^{i\xi/2}, \tag{3}$$

a pulse of constant amplitude, shape, and width.

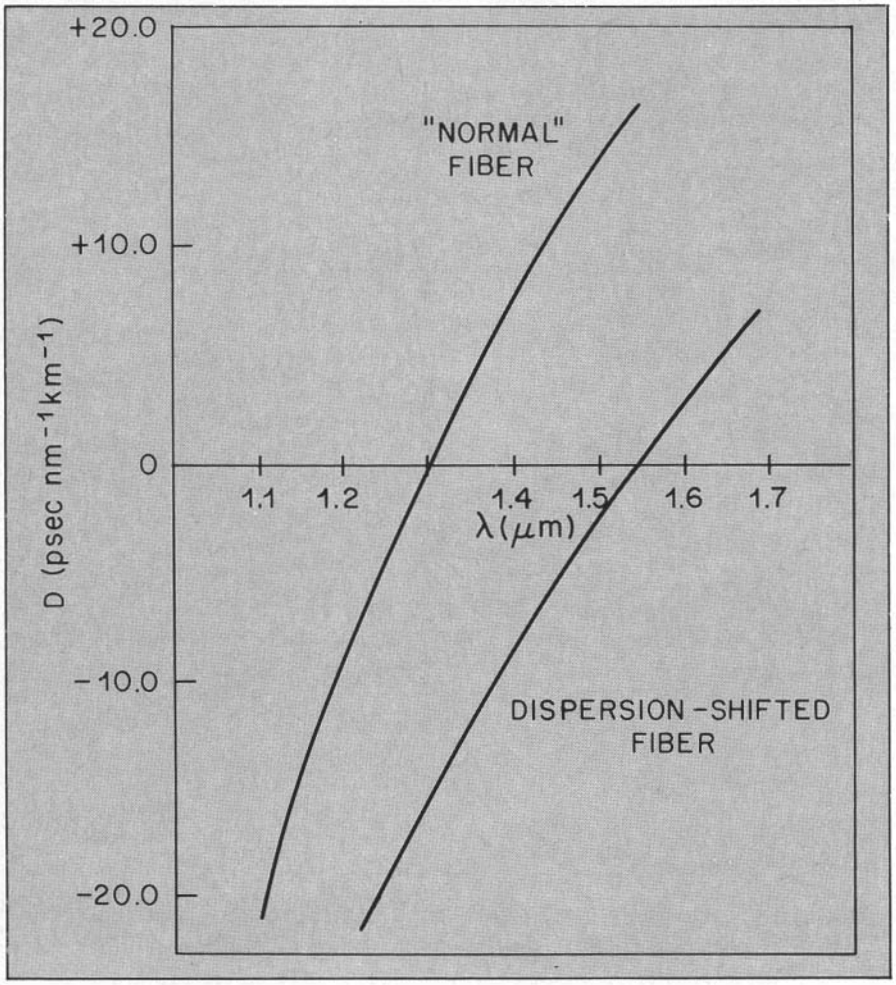

FIGURE 3. Curves of the group velocity dispersion parameter, D, versus wavelength, for both a "normal" and a typical "dispersion-shifted" fiber. The wavelength of zero dispersion can be made to have any desired value greater than ~1.3 μm, through control of the fiber core size and other parameters. Solitons are possible only in the region $D > 0$ ($\partial v_g/\partial\lambda < 0$).

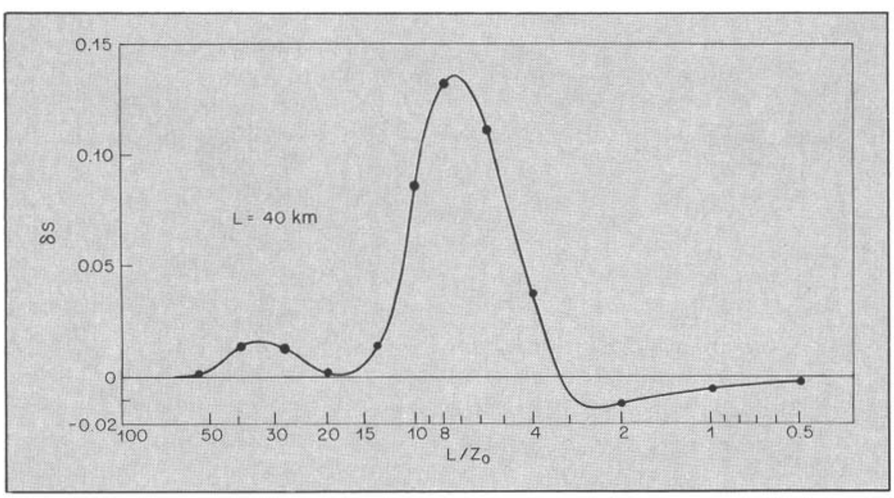

FIGURE 4. Computed change in pulse area (a measure of pulse distortion) obtaining at the end of one amplification period L = 40 km for a perfect soliton launched at input, versus the quantity L/z_0. (For other values of L, only the resonance peak height changes; its location remains the same.[5] Note that the region of "large" z_0 is to the far right, while the region of "small" z_0 is to the far left.

stant energy) will stand up to the periodically varying pulse energy in the system of Fig. 1. Direct numerical solution of the nonlinear Schrödinger equation has provided the answer.[4,5] To discuss the results, however, it is necessary to introduce the quantity z_0, which represents the distance a minimum bandwidth pulse must travel along the fiber (in the absence of nonlinear effects) to be broadened by a factor of about 2. For pulse width τ (full width at half maximum) in picoseconds, group velocity dispersion parameter D (change in pulse delay with change in wavelength, per unit fiber length) in psec/nm/km, and for $\lambda = 1.55$ μm (z_0 scales with λ^{-2}), z_0 in kilometers is given by the expression

$$z_0 = 0.39\frac{\tau^2}{D}. \tag{4}$$

For similar wavelengths, and for silica core fibers, the practical range of D is about 2 to 16 psec/nm/km (see Fig. 3). (In principle, D can be made arbitrarily close to zero, but in practice, small but uniform D is hard to produce.) For that range of D, and for pulse widths ~5–25 psec, z_0 can range from less than 1 to over 100 km.

Figure 4 shows a principal result of the calculations of Ref. 5, the pulse distortion obtained at the end of one amplification period, graphed as a function of the parameter L/z_0. Here the change, δS, of pulse area from its normalized value of unity, is used as a measure of the pulse distortion from a true soliton. (S is the integral of the absolute value of the pulse amplitude envelope function with respect to time.) The peak in δS, occurring at $z_0 \approx L/8$, corresponds to resonance between the soliton's phase term (see Eq. 3 in box) and the periodic pulse energy variation. Note the excellent recovery of the soliton for z_0 both long and short with respect to the resonance value.

Nevertheless, the region of "long" z_0 is the one of practical interest here. First, it allows the soliton peak power, P_1, to be just a few milliwatts, as opposed to the greater power required for short z_0. (P_1 is inversely proportional to z_0; see Fig. 5.) Depletion of the Raman pump power by the signals themselves then becomes negligible, as required for stable gain, independent of the signals. Second, the soliton pulses are exceptionally stable for long z_0. For example, the calculations of Refs. 4 and 5 show negligible increase in pulse distortion after 50 or more amplification periods, and such stable behavior is expected to continue indefinitely. Furthermore, modest lumped losses, such as from couplers, should have negligible effect as long as they, too, are canceled out by Raman gain.

The question is often raised, why not simply propagate the signals at λ_0, the wavelength where the dispersion passes through zero? (See Fig. 3.) For one reason, that scheme would not allow for wavelength multiplexing, because λ_0 corresponds to just one wavelength. More fundamentally, for pulses of reasonable power, the combination of dispersion terms of higher order and index nonlinearity leads to severe pulse distortion and broadening in long fibers.[6] Thus, the soliton is *the* stable pulse.

The maximum propagation distance will therefore be limited not by instability of the solitons, but by the accumulated effects of noise. The most serious of those effects arises from random modulation of the pulse frequencies (and hence of their velocities) by Raman spontaneous emission.[5,7] The corresponding random (Gaussian) distribution in pulse arrival times can lead to significant error if the path is long enough. (Provided the gain is always held close to unity, the Raman spontaneous emission itself increases only in direct proportion to the total path length, and remains negligibly small for many thousands of kilometers.)

In a typical arrangement, the pulses are initially spaced apart by about 10 pulse widths (see Fig. 6). In the first place, this is done to avoid possible interaction between adjacent pulses. But it also helps to provide for a spread in arrival times; as shown in the figure, the detection window can be nearly as large as the pulse separation. It can be shown that for fixed fiber characteristics, and a given error rate, the bit-rate system-length product is a constant.[7] For example, for an assumed error rate of 10^{-9}, for $D = 2$ psec/nm/km, and for reasonable values of the other pertinent fiber parameters, the rate-length product is ~29,000 GHz–km. Thus, for example, for a 4-GHz bit rate (250-psec spacing between 25-psec wide pulses), the

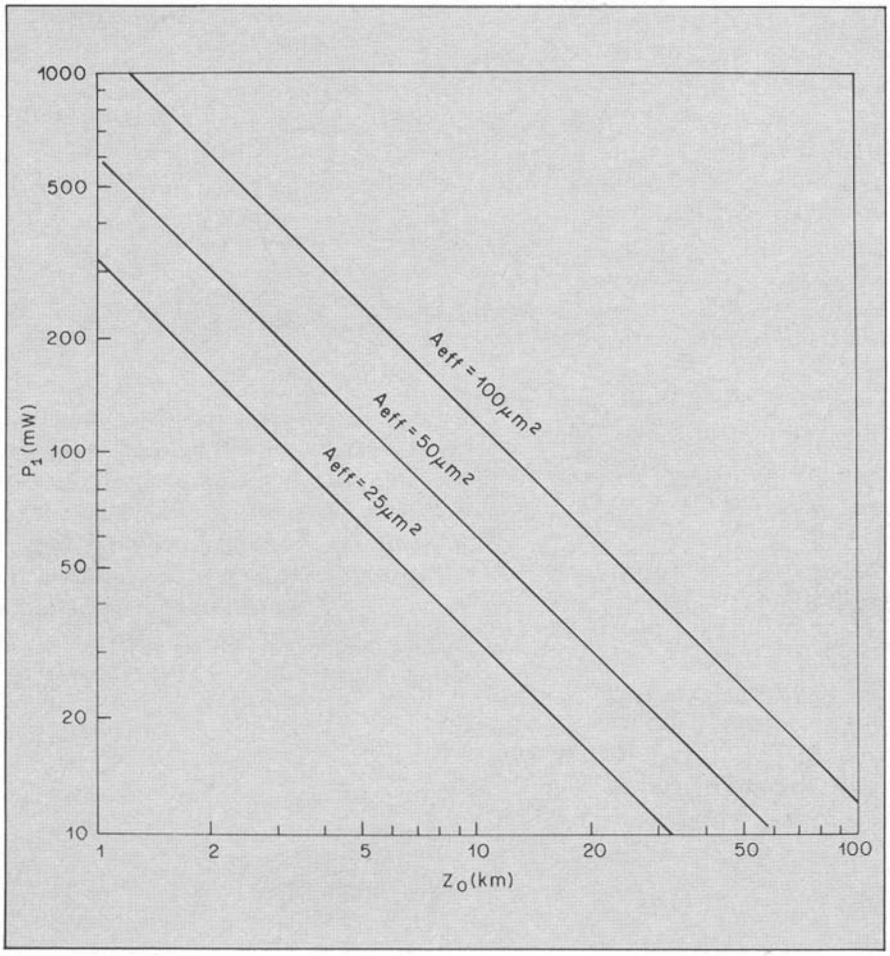

FIGURE 5. Soliton peak power versus z_0 for various effective values of the fiber core area.

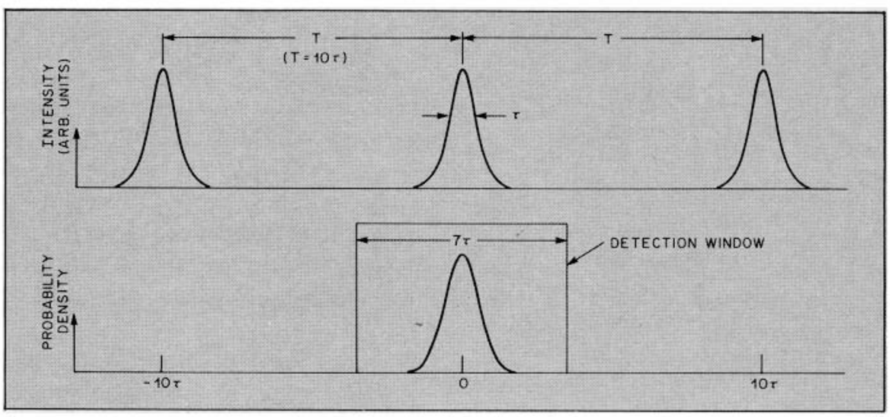

FIGURE 6. (a) Train of pulses in their normal (initial) relative positions. (b) Detection window and corresponding Gaussian probability density of pulse arrival times for an error rate of 10^{-9}.

maximum allowable distance of transmission would be Z = 7250 km.

In contrast to systems involving electronic repeaters, the all-optical system is highly compatible with wavelength multiplexing. By virtue of the fiber's dispersion, however, pulses at different wavelengths will have different velocities and will pass through each other. Hence, it is necessary to consider the possible effects of soliton-soliton collisions. Computer simulation has shown[5] that the colliding pulses modulate each other's velocities, thereby adding a second source of random pulse arrival times. But the effect scales inversely with the square of the frequency difference between the pulse streams. Thus, the variance in arrival times can be made comparable to or smaller than that produced by the Raman noise, just by making the wavelength separation between adjacent channels great enough.

A few examples[5] of system design, with and without multiplexing, are summed up in Table 1. Note that the values of z_0 fall well to the right of the resonance peak in Fig. 4. Note also that the best approach is to use the combination of many channels at a modest rate per channel. (Compare 2b or 2c with 1b.) In addition to producing the highest overall rate-length product, that approach puts the major burden for separating signals on simple optics, rather than on ultrafast electronics. But above all, note the tremendous overall rates made possible by the all-optical nature of the systems: in one instance, the rate is ~106 GHz, or about 2 orders of magnitude greater than possible with conventional systems!

Additional advantages stem from the high and nearly constant signal pulse energies. Thus, for example, the question of error from poor photon statistics never arises in the soliton-based system. Additionally, the system is amenable to the distribution of information over a network, since taps bleeding off just a few percent or less of pulse energy could provide easily detected, low-error signals.

*TABLE 1. **Design examples of high-bit-rate, soliton-based, all-optical systems.***

L = 40 km and D = 2 psec/nm/km

Design No.	z_0 (km)	τ (psec)	P_1 (mW)	Z (km)	N	NR (GHz)
1a	30	12.3	10	3600	1	8.1
1b				2860	5	40.5
2a	100	22.6	3	6600	1	4.4
2b				5200	10	44
2c				3000	24	106

The numbers in this table were derived as follows: Choice of D and z_0 serve to fix τ, through (4), and also P_1. The single channel bit rate R = $1/(10\tau)$, consistent with a spacing of 10τ between pulses. The system overall length Z = 29000/R (see text). The total wavelength span for multiplexing is somewhat arbitrarily set at ~20 nm, and the algorithm for determining N, the number of channels, is detailed in Ref. 5. In examples 1b, 2b, and 2c, Z is reduced, to reduce the variance in pulse arrival times caused by the Raman noise effect; this allows room for the variance caused by soliton-soliton collisions.

Another important advantage of the all-optical system is that only two signal lasers are required per wavelength channel (one for each direction), instead of the hundreds required in a conventional system. In this way the signal lasers could be of higher quality, and still the overall cost would be much less. One excellent candidate here is the fiber Raman soliton laser—a pulse-pumped, closed loop of fiber producing minimum bandwidth pulses of just the shape required for the soliton-based communications system.[8]

The ideas outlined here will soon be given experimental test in a closed loop of fiber whose length will correspond to one amplification period in a real system. Pulses will be injected into the loop, where, as solitons, they will circulate many times. If those experiments are successful, the day of the elegantly simple, all optical communications system cannot be far off.

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