Towards Transoceanic Repeaterless Optical Links

Basilio Catania[1]

ABSTRACT

Present silica fibers have achieved improvements of the repeater spacing x capacity product over traditional transmission systems of a few orders of magnitudes, allowing repeater spacing up to few hundreds Kilometers and capacities up to a few Gigabit/sec.

In particular transoceanic optical cables such as TAT-8 and TAT-9 are expected to cover the 6657 km distance between U.S.A. and Europe with only about 100 repeaters.

Still using silica fibers, a drastic improvement of capacity per fiber can be achieved in the future with multichannel coherent systems; moreover, repeaters' reliability and cost could be greatly improved by the use of optical amplifiers, possibly utilizing active fibers. However, the total number of repeaters to cross the ocean may be only marginally reduced.

Hopes in drastically reducing the total number of repeaters rest on the development of suitable fluoride glasses and relevant sources and detectors operating at approximately 2.4 μm (the "fourth window", following the 0.85μm, 1.3μm and 1.55 μm windows) or, perhaps, at the "fifth window" of approx. 3.5 μm.

Another very interesting development to achieve about limitless bandwidth is that of soliton transmission, which could be applied to both silica and fluoride fibers, now in its first experimentation stage.

The paper gives a survey of the progress made to date and of the foreseeable future achievements.

It was at the Fourth ECOC, in Genoa (1978), that I proposed to describe the merit of a transmission system by a single parameter, given by the product of its transmission capacity times the regeneration or amplification span (assuming compliance to a standard bit error rate). I am glad that many other authors, afterwards, have widely used this "figure of merit" to assess the state-of-the-art of optical fiber transmission systems.

Thus, let me start by noting (Fig. 1) that the figure of merit of today's optical fiber systems has superseded that of coaxial cable systems by more than three orders of magnitude and that of terrestrial radio-relay systems by more than two orders of magnitude. Additional progress is expected in few years from now, still using silica fibers, through the exploitation of coherent multichannel techniques.

Now, since repeater spacing of several hundred kilometers, as well as capacities of several Gb/s, have been achieved, one may conclude that (Fig. 2), at least for a Country such as Italy, the public telecommunication network may be quasi entirely wired with repeaterless optical fiber links.

---

[1] CSELT—Centro Studi e Laboratori Telecomunicazioni SpA (Gruppo IRI-STET), Via G. Reiss Romoli 274, 10148 Torino, Italy. Invited Paper, *Fifth National Symposium on Optical Fibres and Their Applications*, Polish Academy, Warsaw, 21-23 February 1989. Reprinted in SPIE[1] Vol. 1085 "Optical Fibers and Their Applications", 1990

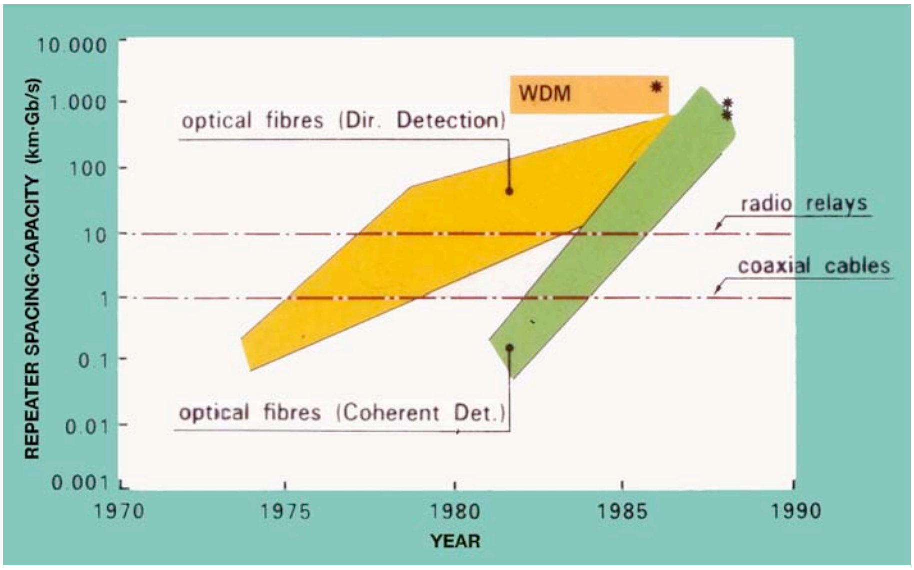

Fig. 1. Evolution of optical fiber systems.

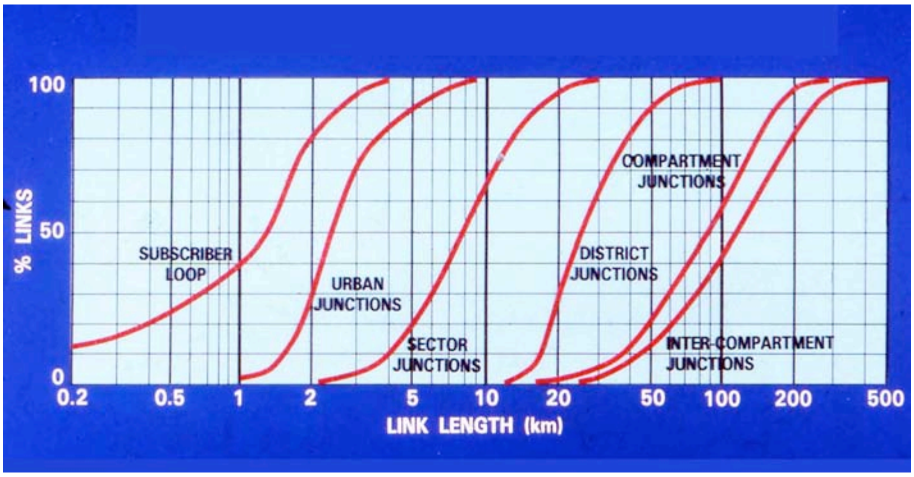

Fig. 2. Link length distribution in public telecommunication network (Italy).

However, even if the same conclusion applies to most of the Nations in Europe, long distance links in other Countries such as USA and Canada, Siberia, Australia, China and Brazil, may still welcome any additional substantial improvement at least in repeater spacing (but also in capacity per fiber), which would allow reducing the number of repeaters and the number of fibers in an optical cable. The need is, however, not so stringent, because, even in said Countries, it is likely to find along the path inhabited spots, if not big cities, every few hundred kilometers. On the contrary (Fig. 3), transoceanic links, as the TAT-8 cable just entered into operation, are in bad need of further progress, as distances range from 30 to more than 50 times those of the average long distance terrestrial link. Crossing the Atlantic Ocean without repeaters, for example, would not only allow a drastic reduction in system first purchase cost, but also to suppress the remote power supply of repeaters, to abate maintenance costs thanks to the increased system reliability and finally to achieve flexibility and expandability, as one could substitute from time to time terminal equipments on the two sides of the ocean with more modern ones, leaving the submerged cable unchanged. Incidentally, towards achieving repeaterless transmission, one could employ more expensive and bulkier equipment on both land sites, with respect to present submerged (distributed) equipments.

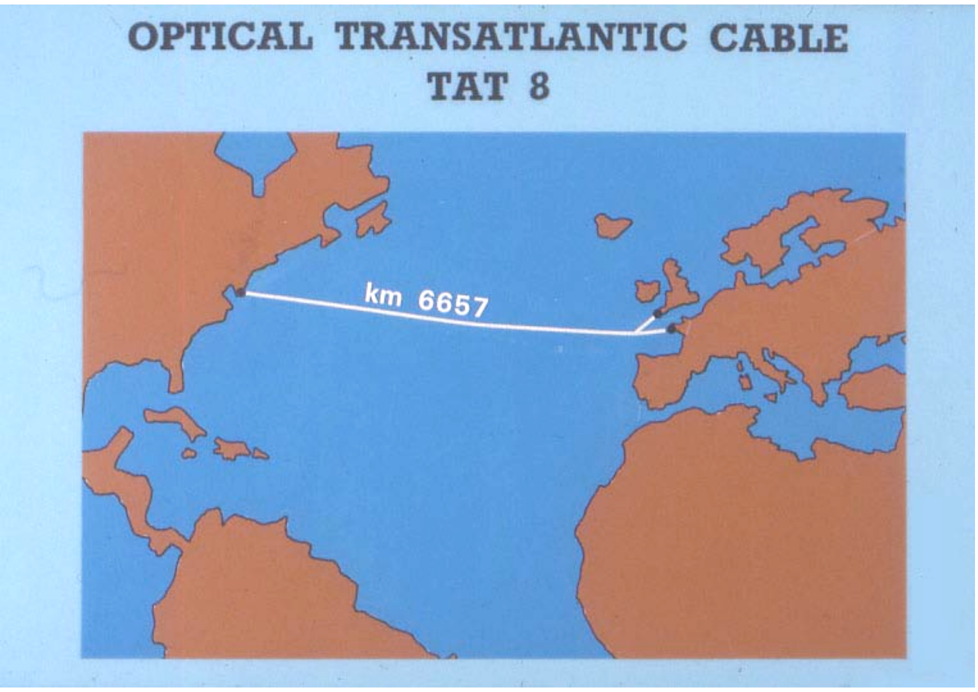

Fig. 3. Optical transatlantic cable TAT-8.

It is interesting to note (Fig. 4) that all copper predecessors of TAT-8, laid down in the Atlantic ocean, have shown a steady reduction in their repeater spacing (and therefore a steady increase of the total number of repeaters) due to the fact that the traffic requirements over the Atlantic were increasing, whereas no revolutionary improvements of technology were taking place. The situation today is that, with TAT-8, 125 repeaters are needed to permit transmission of 7560 standard telephone channels, whereas, with TAT-9, a doubling of that capacity is expected, though employing about the same number of repeaters. Other private optical cables, such as the PTAT-l, PTAT-2 and TATV-l, not shown in the figure, expected to be laid between 1989 and 1992, show similar performances.

In order to investigate the basic requirements of a repeaterless transoceanic optical cable, let us sketch (Fig. 5) the limits imposed to repeater span as a function of maximum bit-rate by both the fiber loss and the total dispersion per unit length. The graph refers to coherent systems with 1 mW injected optical power, 2-PSK modulation and P-I-N photodetectors (dispersion parameter also includes contribution from source's spectral line width). Asterisks in the graph refer to the best reported results worldwide, with reference to silica fibers operating at wavelengths of 1.3 μm and 1.55 μm. However, the graph is applicable to any other wavelength values.

System	Activation year	Cable type	Capacity (tel. chs.) **	Repeater spacing (km)	No. of Repeaters
TAT-1	1956*	2xcoax	48	69	51
TAT-2	1959	2xcoax	48	69	57
TAT-3	1963	coax	140	37	182
TAT-4	1965	coax	140	37	186
TAT-5	1970	coax	845	18,5	361
TAT-6	1976	coax	4200	9,5	694
TAT-7	1983	coax	4200	9,5	660
TAT-8	1988	optical fiber	7560	55	125
TAT-9	1991	optical fiber	15000	70-80	≃100

* Out of service since 1979

** Without compression devices

Fig. 4. Characteristics of transatlantic cables from TAT-1 to TAT-9.

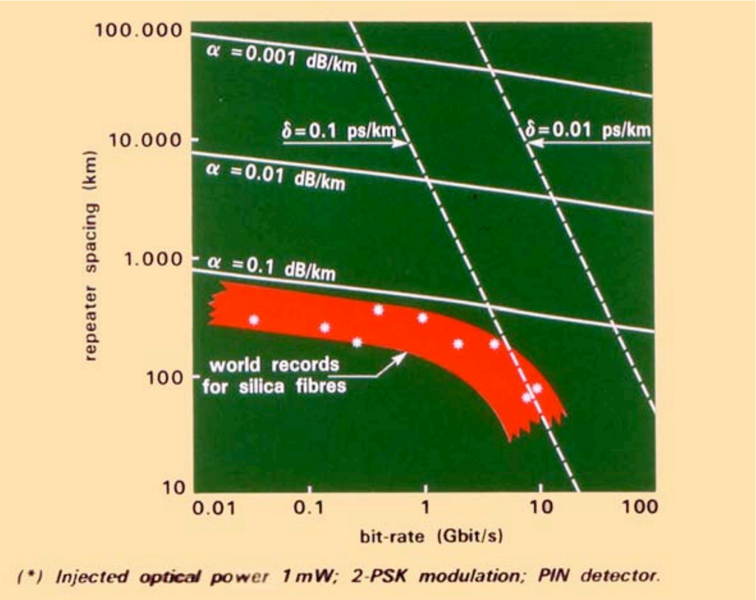

Fig. 5. Repeater spacing vs. bit rate for coherent optical systems

It clearly appears that all present results are limited by a unit loss of approx. 0.15 dB/km and unit dispersion of 0.1 ps/km, which are, in fact, the best possible values achievable with present silica fibers and related sources.

It also appears from the graph that, to achieve transoceanic repeaterless transmission over, e.g., the 6657 km distance of TAT-8 and TAT-9, with the same capacity of TAT-9, we might accept the same unit dispersion of present systems, namely 0.1 ps/km, but we should reduce the unit loss down to around 0.01 dB/km.

We will therefore concentrate first our investigation on the attenuation characteristics of prospective optical fibers. Then we will examine possible improvements on dispersion.

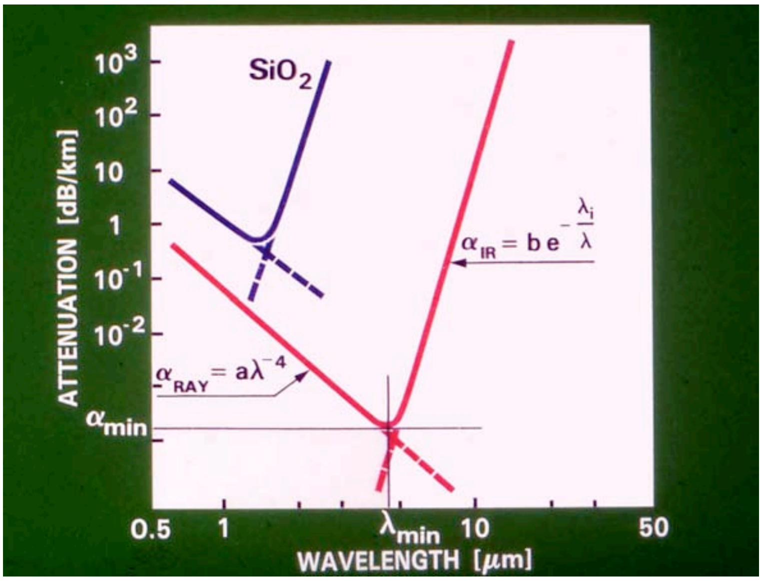

Fig. 6. Minimum attenuation conditions for glass fibers.

It is well known (Fig. 6) that, in the hypothesis that one could completely eliminate impurities from materials used for fibers —and therefore work with the so-called intrinsic loss components—there are two basic sources of attenuation, the first of which (Rayleigh scattering) decreasing with the fourth power of wavelength, the second (vibrational absorption) increasing quite steeply with wavelength, as this approaches a characteristic wavelength of the material which we will call “vibrational wavelength”, in that it is determined by the atomic vibrational modes in the material lattice.

It is also apparent from the graph that the wavelength λ_{min} corresponding to minimum loss is very near to the crossing of the two curves and that the minimum attenuation α_{min} is slightly above the scattering loss at wavelength λ_{min}. To reduce α_{min} requires to reduce either or both loss components but that inevitably leads to an increase of λ_{min}: in other words, reduction of fiber loss inevitably requires to work at longer wavelengths, provided that we can find suitable materials, either than silica, exhibiting more favorable values of the three constants a, b and λ_i, and related sources and detectors.

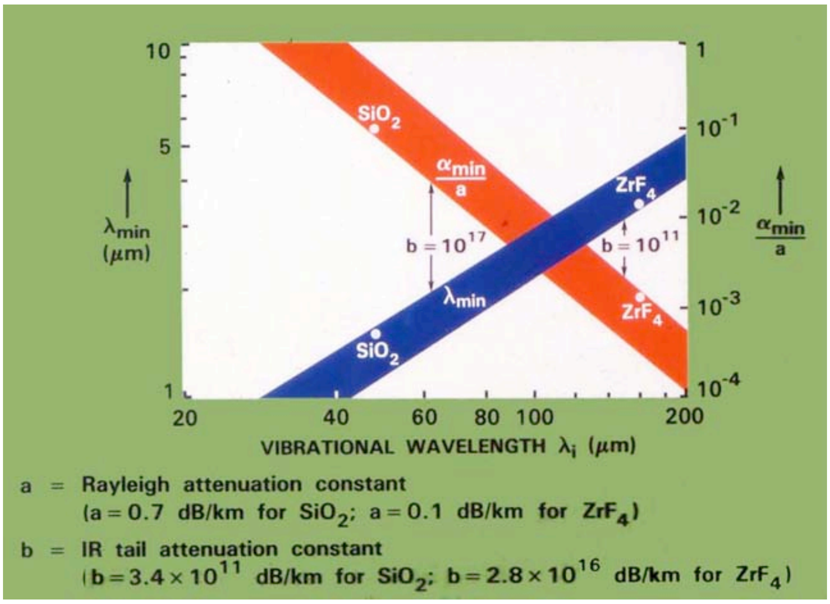

Fig. 7. Minimum attenuation α_{min}, and minimum attenuation wavelength λ_{min} for glass fibers.

Results of calculation of minimum loss conditions are shown in Fig. 7, where both α_{min}/a and λ_{min} are plotted as a function of λ_i, for a broad range of values of the vibrational loss parameter b.

The graph shows a strong dependence of both α_{min}/a and λ_{min} on the vibrational wavelength of the material λ_i, whereas the dependence on b appears to be of minor relevance. In other words, the paramount requirement to obtain low attenuation, is to work with material structures that can vibrate at much lower frequencies (or longer wavelengths) than silica, which latter exhibits a λ_i value of around 48 μm. If, for example, we could work with fluorozirconate glasses, exhibiting a vibrational wavelength of around 163 μm, we could obtain more than one order of magnitude reduction of the α_{min}/a ratio. As, moreover, the scattering parameter a equals 0.7 dB/km·μm^4 for silica and 0.1 dB/km·μm^4 for fluorozirconate glasses, this gives a further advantage of 7:1 to these latter glasses with respect to silica. It is to be noted that the scattering parameter a (which expresses the unit scattering loss at a wavelength of 1 μm) essentially depends on the rheological characteristics of the material and it is as low, as lower is the softening temperature and the so-called isothermal compressibility of the material. In other words, it is desirable to obtain the amorphous structure, which is typical of glasses, in the most smooth way, in order to reduce the appearance of inhomogeneities, which are responsible for the scattering losses.

It may be interesting to look at the microscopic structure of the two above mentioned materials (Fig. 8), from which it clearly appears the intrinsically heavier elements and longer strings of fluorozirconate glasses, both leading to longer wavelength vibrations (hence lower minimum attenuation) with respect to silica.

It is, however, to be remarked that theoretical results, as those shown before, which are aimed at inventing a suitable material—so to say—or at least to help in selecting suitable materials from those already known, must be complemented by the consideration of other extrinsic factors, not considered above. For example (Fig. 9), both zinc-chloride and potassium-chloride glasses, though exhibiting lower minimum attenuation with respect to fluoride glasses, show excessive tendency to OH inclusion (as all chlorides do) as well as to recristallization, therefore their lower theoretical attenuation is of no value, in practice.

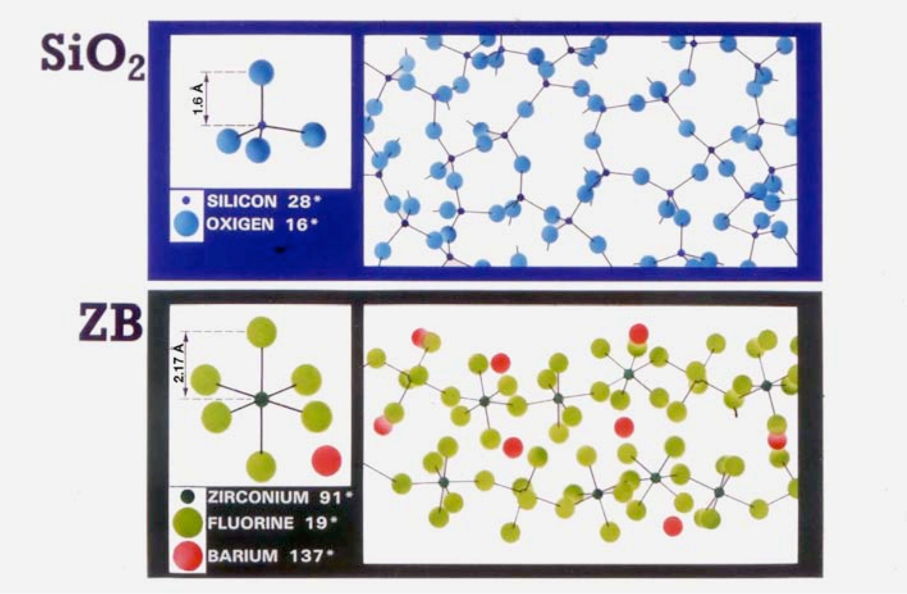

Fig. 8. Structure of silica and fluorozirconate glasses.

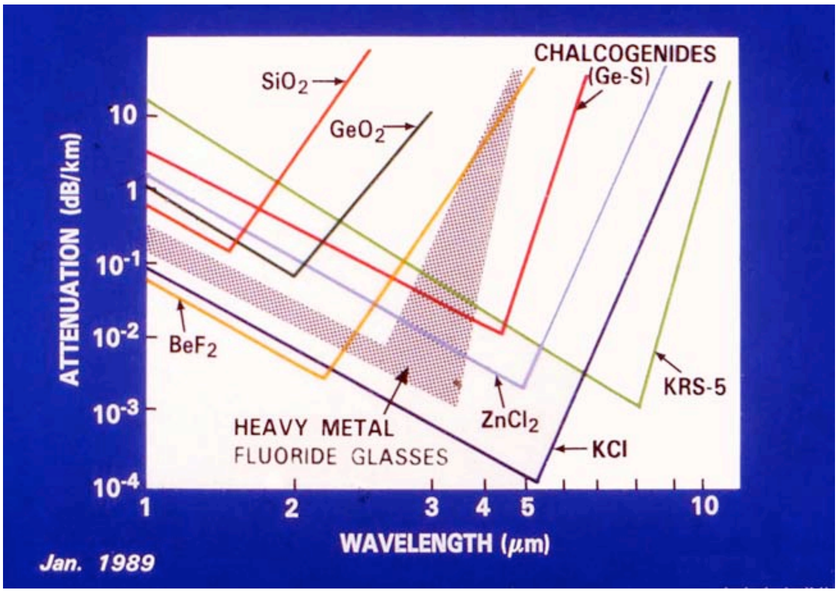

Fig. 9. Theoretical attenuation of MIR fibers.

Another important factor affecting the choice of a suitable material is its dispersion characteristic, which, together with the source spectral line width, limits the maximum transmittable bit-rate.

As known, all glass materials exhibit a zero-dispersion wavelength λ_0 (Fig. 10), which is inversely proportional to the square root of the product of two energies, one of which E_g* is not much different from the energy gap of the material and the other E_l corresponding to the energy of the lattice oscillator. Although in Fig. 10 energy gaps between 10 eV and 16 eV are shown, in practice they vary much less (E_g* = 12.76 eV for silica and 12.88 eV for zirconium tetrafluoride). On the contrary, the lattice oscillator energy E_l varies quite widely, ranging, e.g., from $E_l = 0.132$ eV for silica to $E_l = 0.082$ eV for zirconium tetrafluoride. However, the graph shows that the zero dispersion wavelength does not change much, at least not as much as it would be desirable to work at the minimum loss wavelength. In fact this graph shows that moderately increases from 1.27 μm of silica to about 1.6 μm for zirconium tetrafluoride, this latter being far away from the approx. 3.5 μm wavelength corresponding to its minimum loss wavelength of around 3.5 μm.

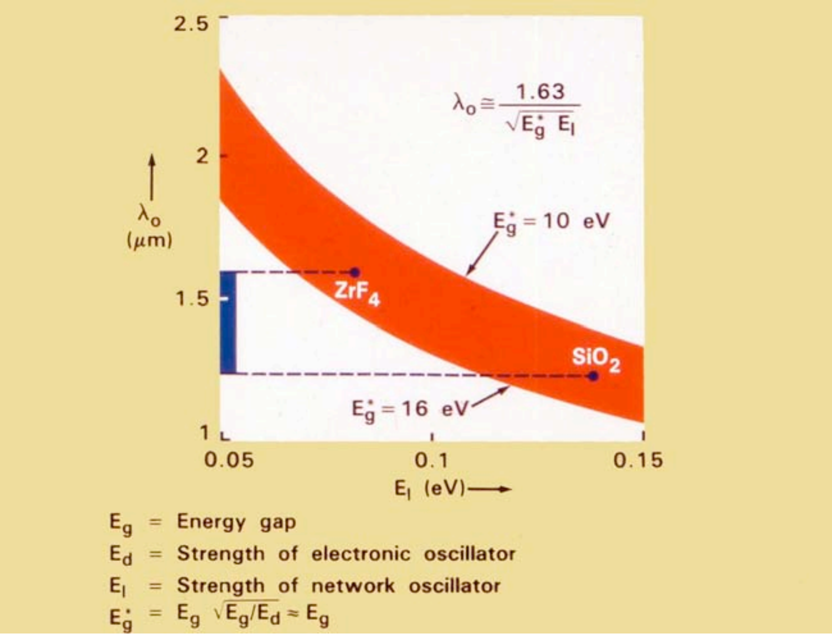

Fig. 10. Zero-dispersion wavelength λ_0 of glass fibers.

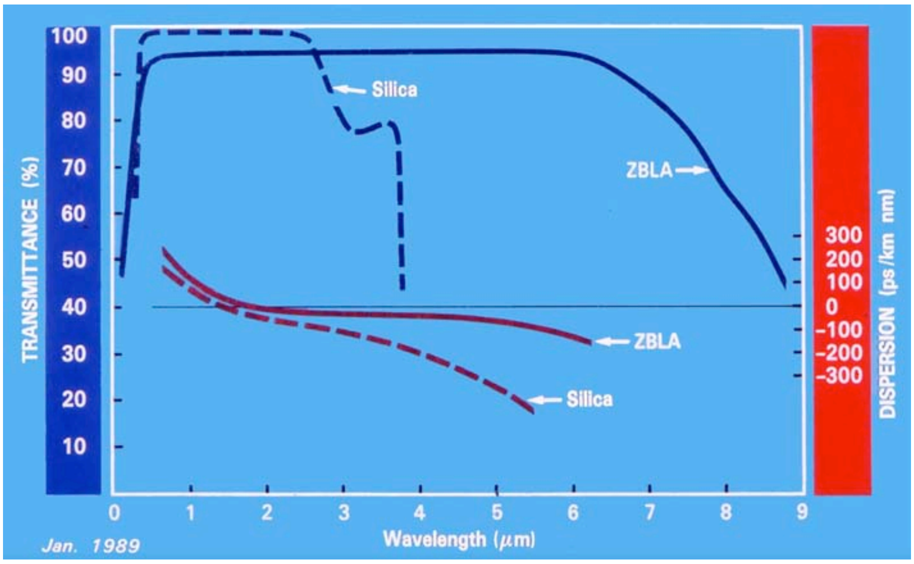

Fig. 11. Spectral characteristics of fluorozirconate ZBLA glasses.

Fortunately (Fig. 11), both the absolute value and the slope of dispersion with respect to wavelength of this material are much less than the corresponding values for silica glasses. Therefore, it should be easy to compensate that low dispersion of fluoride glasses with a counter-dispersion obtainable through suitable shaping of the refractive index profile, as it is done today to move the minimum dispersion wavelength from 1.27 μm to 1.55 μm for silica fibers. This, nevertheless, prevents working, in general, at very long wavelengths, as it would be suggested from pure minimum attenuation considerations.

On the other hand, very long wavelengths may also lead to unacceptable fiber cross-sections and elasticity module, which would impair mechanical characteristics of the fiber. The consequence of all the above is that we should expect to work at wavelengths, say, below 6 μm. For example, for fluoride glasses, even if the minimum attenuation has been shown to lay around 3.5 μm, we should expect to work at somewhat lower wavelengths, in the range of 1.6 to 3.5 μm though largely achieving the 0.01 dB/km target set before.

Of course, finding a suitable glass material for fibers is not enough, in that we need sources and detectors operating at the selected wavelength with adequate power and sensitivity, respectively.

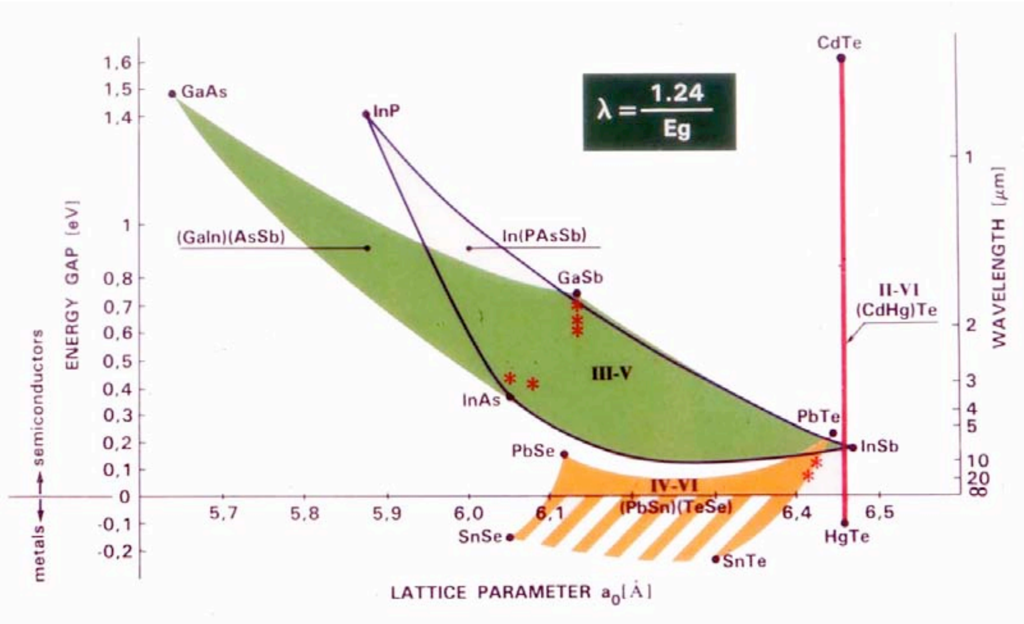

Fig. 12. Optoelectronic materials for MIR optoelectronic devices.

Fig. 12 shows two families of semiconductor compounds which may be adequate for the wavelength range quoted above: the Ill-V and the Il-VI compounds. A third family, that of IV-VI compounds could be considered for wavelengths above 6 μm which do not seem practicable for repeaterless transoceanic links, for the reasons outlined above.

May I remind you that the operating wavelength λ in μm for said semiconductors is deducible from their energy gap E_g in eV by the simple relation $\lambda = 1.24/E_g$. Both λ and E_g are reported in the vertical scales of the diagram. Abscissas show the lattice parameter of the semiconductor compound. Various types of antimonides and of Cadium-Mercury-Tellurides have been already reported in the literature (shown with asterisks in the graph).

Three lasers of the III-V family, with encouraging characteristics have been developed around 2 μm and two around 3 μm. The two shown in the IV-VI family, working at 8 μm and 10 μm respectively, have been developed for spectroscopy applications.

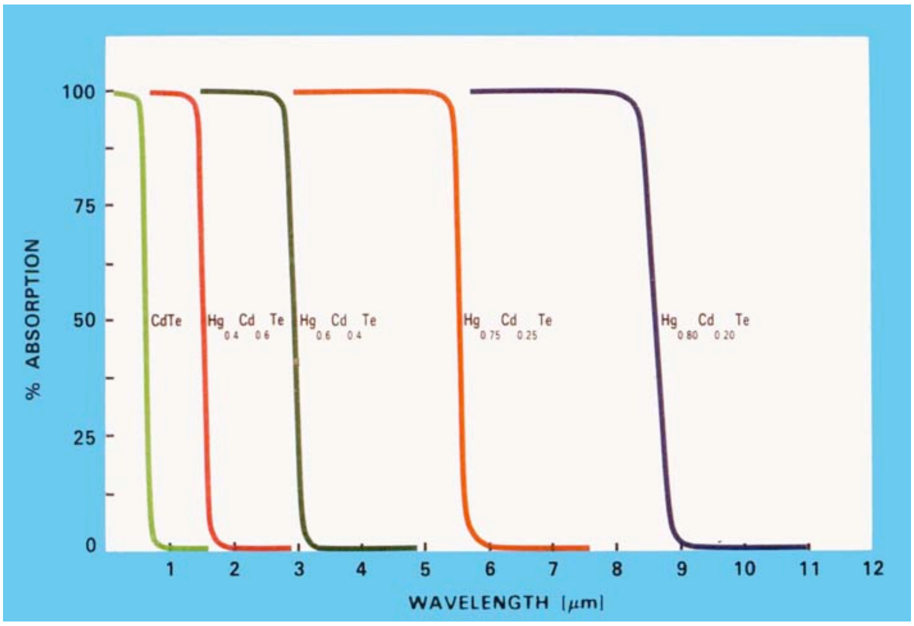

Fig. 13. Coverage of MIR range by CMT photodetectors.

As for photodetectors, they mostly pertain to the II-VI family and can be constructed with a whole range of wavelength up to 10 μm. More precisely, with cadmium-mercury telluride semiconductors, by increasing the mercury content and decreasing the Cadmium content in Tellurium matrix (Fig. 13), longer wavelength operation can be achieved. Good avalanche CMT photodetectors have already been developed at 1.3 μm wavelength and there appear no reasons why they should not be extended to 2.5 μm operation with similar performance. Another promising candidate material for avalanche photodetectors operating at 2.5 μm wavelength is the Ga Al As Sb (gallium/aluminum arsenide antimonide) from the III-V family.

CSELT Laboratories have achieved very good results in CMT materials, as shown in Fig. 14. Our patented LPE process allows to easily obtain any composition of the CMT material, to cover the entire 1-lo 1um wavelength range, with substrate size up to 4 cm .

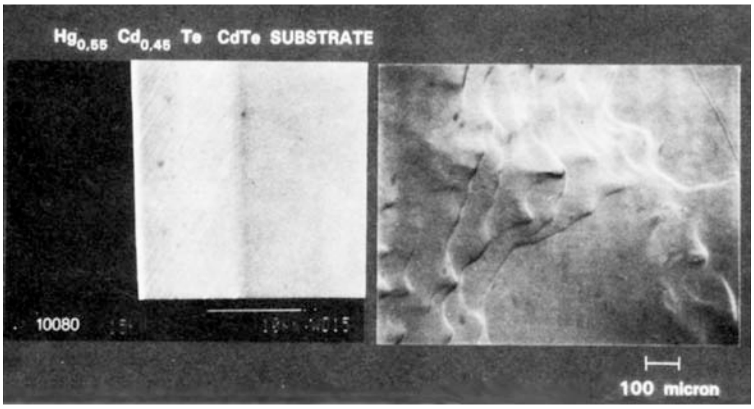

Fig. 14. SEM photograph of CMT material developed at CSELT.

In our laboratories we also work on flurozirconate glasses, though achieving attenuation values which are still far from the minimum theoretical value of about 0.001 dB/km or even from the 0.01 dB/km value required for making a repeaterless transatlantic cable. Fig. 15 shows two preforms recently obtained at CSELT, which have not yet been drawn into fibers, but exhibit good transparency and should permit us to achieve kilometer lengths of fiber fabrication. In other laboratories unit loss of few tenths of dB/km has been demonstrated over some tens of meters of fiber length and also a scattering loss of fluoride glass material around 0.01 dB/km has been measured, at 2.5 μm wavelength.

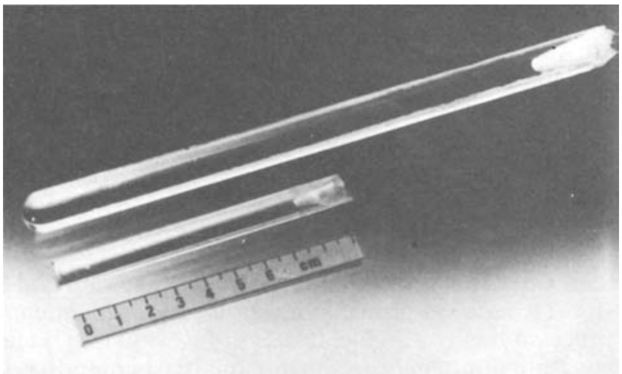

Fig. 15. Preforms of fluorozirconate glass developed at CSELT.

Apart from the purification of materials, one main difficulty to be overcome in drawing fluoride fibers is the stringent control of the drawing temperature, one order of magnitude better with respect to that required to draw silica fibers.

However (Fig. 16), if we look back at the history of silica fibers we may see that more than ten years of intense effort from prestigious research laboratories in the world was needed to reach the theoretical attenuation limit, since the famous breakthrough made by Corning Glass Works in 1970. Forecasts for fluoride glasses (first fabricated in 1974) are to achieve around 0.02 dB/km loss in three years from now, which result would permit to achieve around 1500 km repeater spacing, therefore, to cross the Atlantic Ocean with only three repeaters.

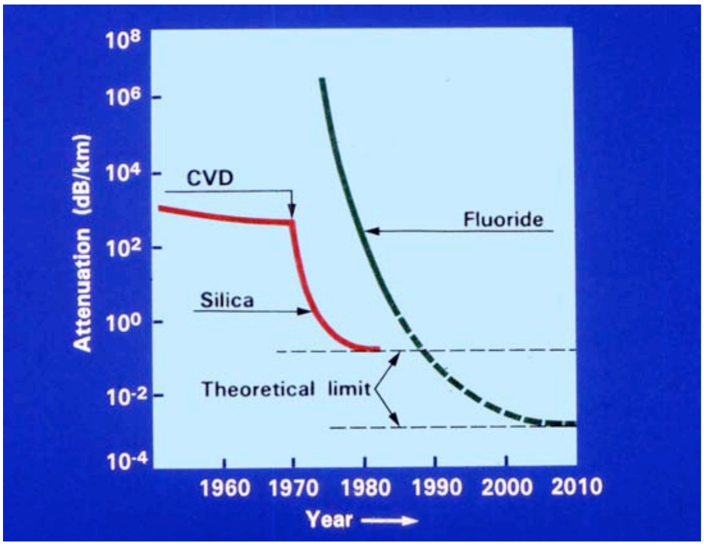

Fig. 16. Progress in optical fiber fabrication.

Incidentally, these repeaters could be of a much simpler type, i.e. mere optical amplifiers, realized with a short length of active fiber optically pumped by a low cost laser, of which laboratory prototypes with remarkable performance have already been demonstrated. Fig. 17 shows one of such amplifier's laboratory set-up, at CSELT, for the 1.55 μm wavelength, which is now being considered for submarine optical cables to be used in the Mediterranean sea. In fact, the use of optical amplifiers, instead of electronic regenerators with optoelectronic transducers, would drastically improve the reliability and cost of optical cable links and also reduce the power drain from the remote power supply system.

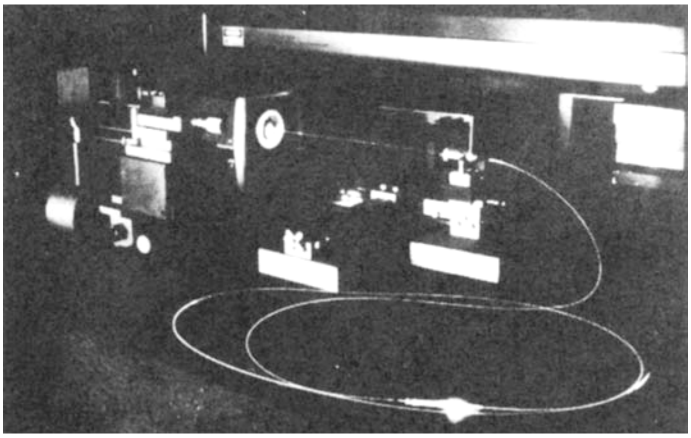

Fig. 17. Optical amplifier at 1.55 1 μm developed at CSELT.

This solution seems, in many experts' opinion, even more commercially viable, in the short-medium term, than the repeaterless solution, mostly because of the difficulties arising from the splicing losses of MIR fibers, once a satisfactory fiber attenuation will be achieved. In fact, even if a few tens of kilometers of continuous length of such fibers could be fabricated, several hundred splices would be required to cross the Atlantic, and therefore the sum of all splicing losses would become predominant with respect to the overall fiber loss.

Before ending my presentation, let me touch upon that very exciting subject of soliton transmission by first noting that solitary waves, or solitons, have been in existence in nature long before human beings have realized their importance for information transmission. I am not merely referring to solitary waves travelling on water as those first observed in 1934 by John Scott Russell along 2 miles in a

Scottish canal, nor to those underwater solitary waves, detected by Alfred Osborne in 1980 in the Sulu Sea (between Borneo and the Philippines) and travelling at unusually high speed with intact shape for several hundreds kilometers. I refer to communication among organic molecules, such as proteins, which undergo stereoisomeric binary transformations (i.e. they change between two shapes, without changing chemical composition), when hit by an energetic solitary wave, which features several distinctive characteristics, similar to those of water solitary waves, quoted above.

Their existence has been detected by Albert Lawrence of the Hughes Aircraft Corporation in protein molecules, by the use of light scattering. Other scientists, as John Wehrung and James Mc Alear of Gentronix in the USA, say that they found good evidence that there is no interference upon collision of two such solitary waves in organic molecules and that they travel through conserving their shape and without losing energy, though over the relatively short distance between molecules. Robustness of solitons towards external perturbations such as electromagnetic fields is also envisaged. For all these reasons, biomolecular computers operated by solitons have recently been considered, whereby photons would be used to both create and detect such solitons.

In other words solitons seem to possess a universal property of coming into existence as a distribution of either matter or energy in spacetime—i.e. as packets of massive or massless particles— as a result of the nonlinearity of the transmission medium affecting the propagation speed. They therefore seem to be the intrinsically preferred waveform of the material as shown, in mathematical terms, by the solution of the nonlinear wave equations, such as the KdV (Kortewegs-de Vries) for water waves and the non linear Maxwell-Schrödinger equation for electromagnetic waves. Moreover, as they tend to reach and maintain their shape in spacetime, no need exists for repeated standardization of duration and amplitude of signal waveforms, as required for transmission of binary signals and calling for use of regenerators. So, why create, through clipping amplitudes and steep-rising wave fronts, frequencies that the material can hardly transmit, instead of creating a waveform that the material can maintain forever and everywhere?

As for optical soliton transmission through fibers, a very remarkable laboratory demonstration has been made last year by Linn Mollenauer and Kevin Smith of ATT Bell Laboratories through launching 50 ps wide soliton pulses at a rate of around 2 Gbit/sec through a single mode silica fiber. To compensate for fiber loss, Raman amplification was used every 40 km, in a loop set-up, without need of any electrical regenerator up to a total span of 4000 km (most recent results, shown in Houston this month, are 6000 km). As known, Raman gain is obtained by injecting a continuous wave laser power (ca. 100 mW) into the fiber, at a slightly different wavelength (ca. 100 nm) with respect to the signal wavelength: as the injected optical power is high enough to bring the material into non linearity, a fraction of it is transferred to the signal wavelength and thus the fiber acts as its own amplifier. Obviously, any other optical amplification scheme may have been adopted.

If, however, MIR fibers of the type described above would have been available to Mollenauer and Smith, they might have achieved soliton transmission over several thousands kilometers without the need of optical amplification. At CSELT Laboratories solitons at 1.55 μm with 15 ps duration have been obtained (Fig. 18) with spectrum shapes and corresponding time autocorrelation very near to the theoretical shapes. May I remind you that both frequency spectrum and waveform of solitons are of the squared hyperbolic secant type, which is very similar to a Gaussian pulse with somewhat steeper wave fronts. Fig. 19 shows the laboratory set-up to obtain solitons. The figure of merit of soliton transmission is estimated to be around 60,000 km·Gb/s, therefore more than another order of magnitude would be gained above the best reported results of present coherent transmission systems, without using wavelength multiplexing. The above figure could be extended by another order of magnitude with wavelength multiplexing, thus permitting transoceanic repeaterless transmission of 100 Gb/s streams per single optical fiber.

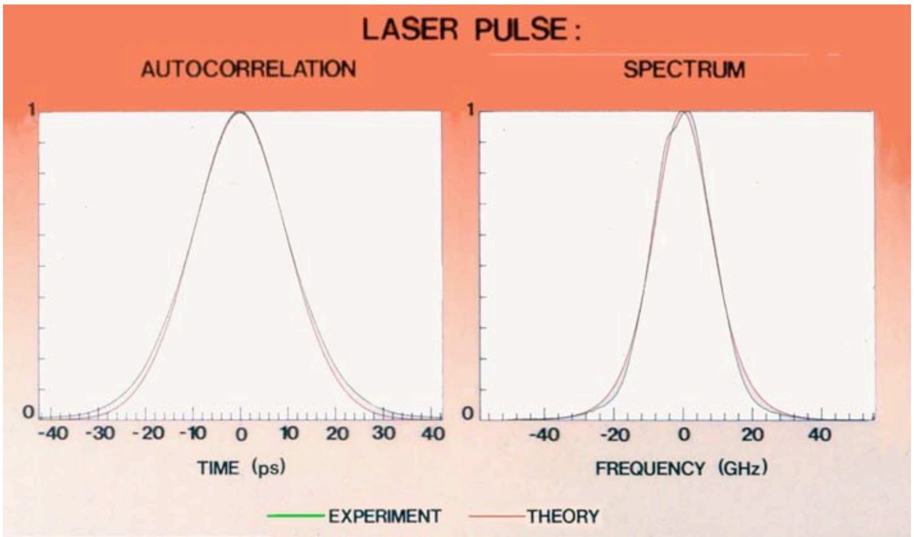

Fig. 18. Autocorrelation and frequency spectrum of 15 ps solitons produced at CSELT.

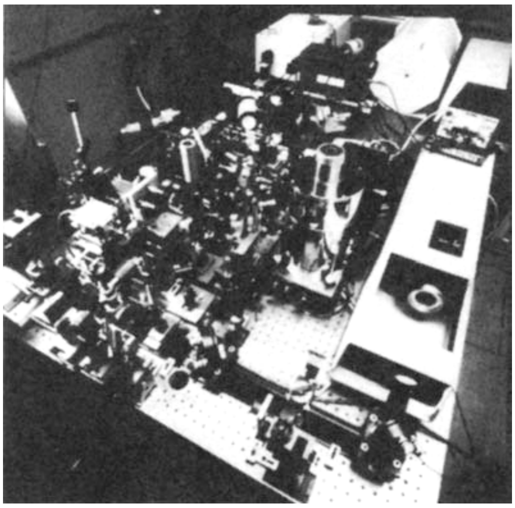

Fig. 19. Laboratory set-up to produce 15 ps solitons at CSELT.

Dream or reality? In a paper of three years ago, Mollenauer and coworkers maintained that the use of solitons in long-distance all-optical systems is not only more convenient or economical but rather the *only* viable solution. That paper, in fact, only reported results of computer simulations—which were quite exciting; but, two years later, it was followed by that laboratory experiment mentioned above. Therefore the excitement continues, but even more our admiration for the miracles of nature.