Undersea Fiberoptic

Cable Systems:

High-Tech

Telecommunications

Tempered By A Century

BY NEAL S. BERGANO

Of Ocean Cable Experience

Undersea fiberoptic cables make international communications possible. The challenge is to develop new approaches to increase capacity and keep up with demand.

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In today's Internet age, information flows across continents as easily as it flows across the office. With so many "point and click" virtual connections, it's easy to forget that the world's communications needs are made possible by real systems, based on fiberoptic cables. This of course comes as no surprise to members of the optics community; however, many others underestimate the importance of undersea fiberoptic cables for intercontinental telecommunications. Anyone who makes international phone calls, sends international faxes, or simply surfs the web at sites in other continents uses undersea fiberoptic cables.

Although the debate regarding the merits of cable systems versus satellite systems for international communications ended many years ago, with cable systems the clear economic and technological winner, most people still assume that overseas communication occurs via satellite. But consider this: in the 1990s, over 350,000 km of undersea fiberoptic cable has been installed across the world's oceans.
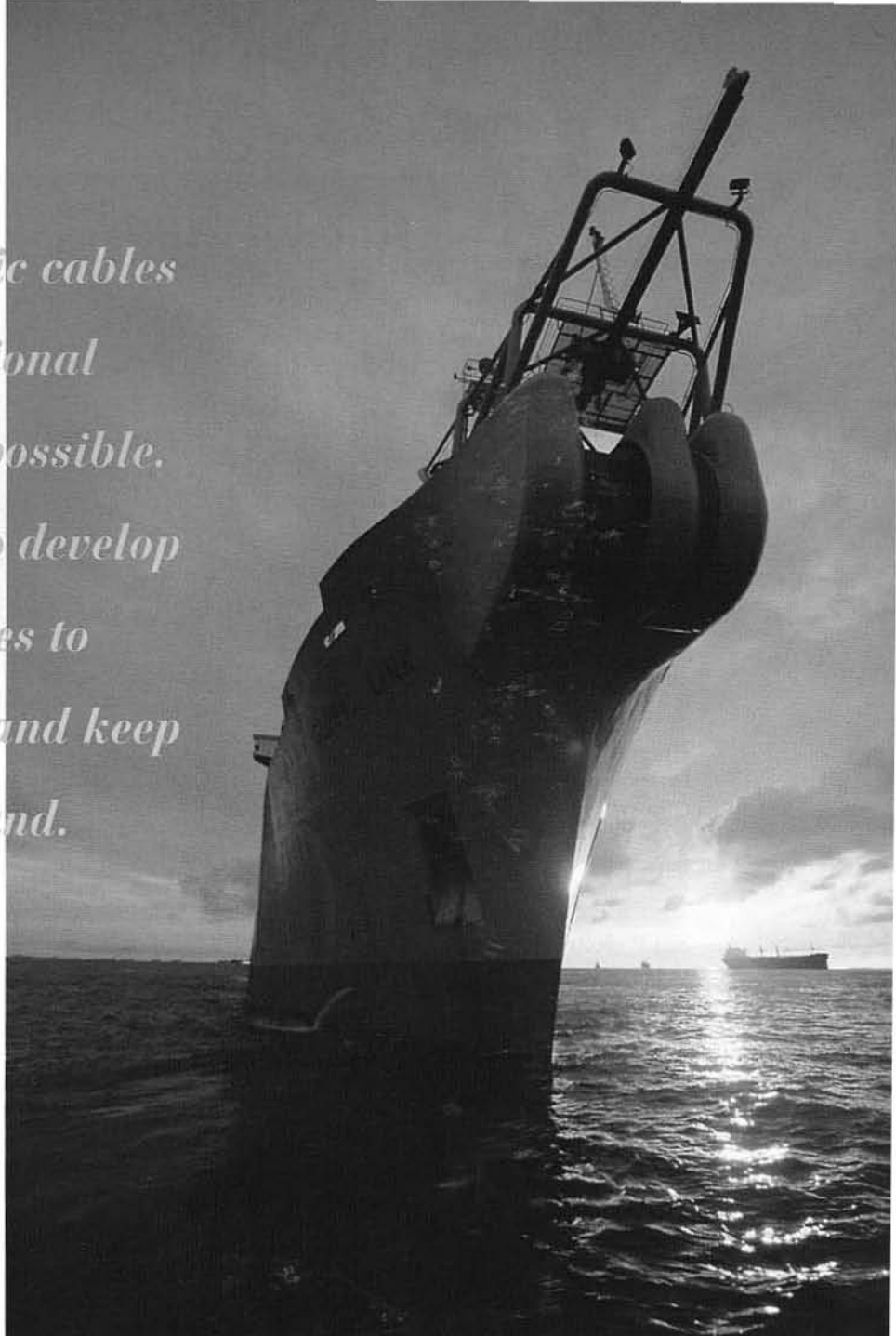
The potential capacity of fiberoptic communications has been understood for 30 years; however, only with the introduction of optical amplifiers and wavelength division multiplexing (WDM), the simultaneous transmission of signals at many wavelengths, has this potential been translated into installed capacity.

Two critical factors are responsible for what I call our "Golden Age of Fiberoptics:" the insatiable *demand* for digital capacity spurred on by the Internet and the *availability* of capacity created by fiberoptic technology. As the pace of cable installations accelerates and the capacity of each fiber increases faster than Moore's law, the undersea cable industry is sharing in this Golden Age.

A rich history of undersea cables

The first successful transatlantic telegraph cable connected North America to Europe and went into service

in 1866, 34 years after Samuel Morse invented the telegraph. At that time an experienced telegraph operator could send about 17 words per minute, at a cost of about $5 per word.[1] Nearly a century passed before the first transatlantic telephone cable (TAT) went into service in 1956, providing 48 telephone circuits between Newfoundland and Scotland.[2] These analog systems were based on coaxial cables with electronic amplifiers. By 1983, the analog cable systems had grown in capacity to over 4200 voice circuits. These circuits were transmitted by frequency division multiplexing many circuits over an electrical bandwidth of a few tens of megahertz. The signals were boosted in "wideband" electrical amplifiers that were placed in repeaters and spaced every 9.5 km. In an interesting twist-of-fate, the cable in the coaxial systems was lin-

Figure 1. Raising the bight of the 1865 cable above the surface.

ear, while great design efforts were expended to cope with the nonlinearity of the electronic amplifiers, which is the opposite of the present optically amplified fiberoptic systems.

Between 1988 and 1989, the first undersea fiberoptic systems, with a capacity of 280 Mb/s on each of three fiber pairs, were installed across the Atlantic and Pacific oceans. These were hybrid optical systems in the sense that the repeaters converted the incoming signals from optical to electrical, regenerated the data with high-speed integrated circuits and re-transmitted it with a local semiconductor laser. The transmission capacity of the regenerated fiber cables eventually increased to 2.5 Gb/s, and repeater spacing increased with the switch from 1.3 μm multi-frequency lasers to 1.55 μm sin-

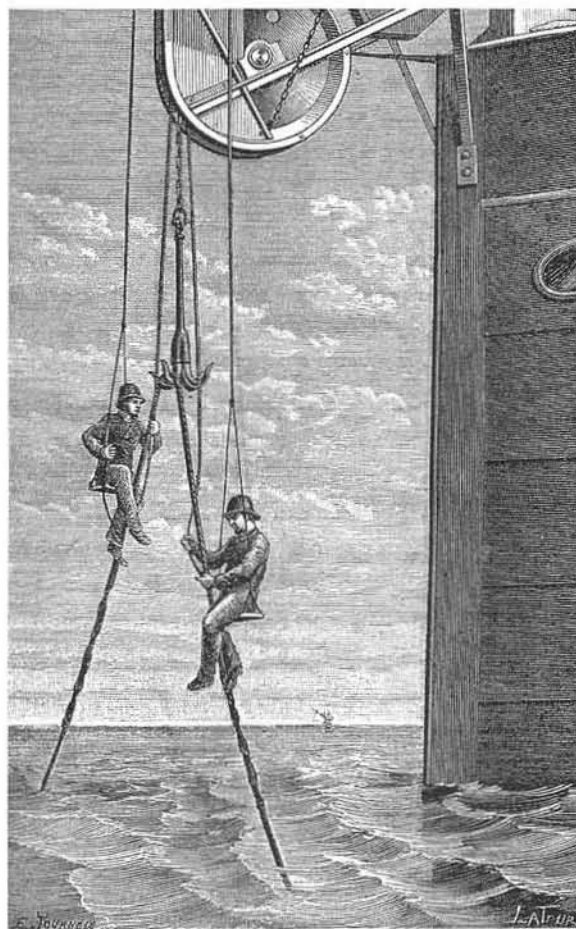gle-frequency laser diodes. These first undersea fiber systems revolutionized international telephony, bringing costs down and greatly expanding capacity and quality. However, the undersea repeaters' electronic processing made it difficult to exploit fiber's large bandwidth. Beginning in the mid-1990s, undersea fiberoptic systems were deployed that used erbium-doped fiber amplifiers (EDFAs) in the repeaters. These systems removed the electronic bottleneck and provided the first clear optical channel connectivity between the world's continents.[3]

Modern undersea cable systems

Today's undersea systems use EDFAs to compensate for signal loss in the optical fiber cable. These optical amplifiers are in repeaters that are typically spaced every 50 km along the cable and have an optical bandwidth wide enough to support multiple optical channels using WDM techniques. For transoceanic transmission, data signals coming from land-based systems (typically referred to as "terrestrial" systems) are converted to an optical format that is more robust. Systems that will be deployed in the next few years will support many 10 Gb/s data channels. Since cables are typically installed with several pairs of fibers, the total capacity of these new cables will be several terabits per second. For example, the Hibernia Undersea Cable System being built for Worldwide Fiber International will go into service in the first quarter of 2001: each of the two transatlantic cables has a targeted capacity of forty-eight 10 Gb/s WDM channels on each of four fiber pairs. This could provide nearly 2 Tb/s of fully protected capaci-
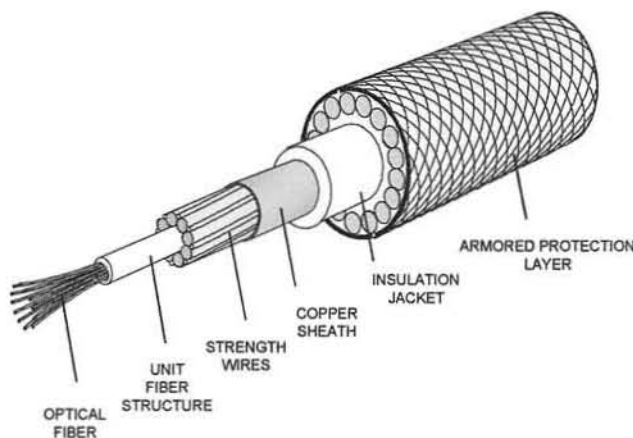

Figure 2. Cutaway diagram of a cable section.

ARMORED PROTECTION LAYER

INSULATION JACKET

COPPER SHEATH

STRENGTH WIRES

UNIT FIBER STRUCTURE

OPTICAL FIBER

ty across the Atlantic Ocean and will be a key factor in meeting the demand for Internet capacity between Europe and North America. The two transatlantic cables will be approximately 6000 km in length, and will connect points in Halifax, Canada; Boston, Massachusetts; Dublin, Ireland; and Liverpool, England.

Undersea fiberoptic cables are still deployed by cable laying vessels that typically have enough storage capacity to lay an entire 6000 km transatlantic cable in one run. The majority of the cable is designed for deep-water operation up to a depth of 8 km. This cable has the smallest diameter since deep water is a fairly benign environment. Armor wires are added to the cable to increase its strength in areas where more mechanical protection is required (Figure 2). Near the coast, the cable is buried to prevent accidental cable cuts from heavy equip-

Figure 3. Loading repeaters at Simplex Technologies.

ment such as fishing rigs or ship anchors. The optical amplifiers, including pump lasers, and other components are housed in beryllium-copper pressure vessels that can withstand in excess of 10,000 psi, the pressure encountered in deep water (Figure 3). The active components (such as pump lasers) are powered by running a simple DC current through the copper conductor in the cable. The power feed equipment at the shore terminals supply a constant current of about 1 amp at ~10,000 V, where one side of the cable is biased with positive voltage and the other with negative voltage.

From an optical standpoint, the undersea portion of the system is sometimes referred to as an "amplifier chain;" it is a concatenation of optical amplifiers and cable spans. The attenuation or loss in optical fiber is 0.2 dB/km (at 1550 nm); thus, in a 6000 km long transatlantic system, the optical amplifiers will compensate a total of 1200 dB of cable attenuation! For proper system operation, the gain in the amplifiers must match the attenuation in the fiber exactly. At first this might seem like a difficult task; however, the solution comes almost for free from the gain characteristics of the optical amplifier. One of the many advantages of the EDFAs is the ability to be operated deep into gain compression without any significant distortion of the high-speed data signals being transmitted.
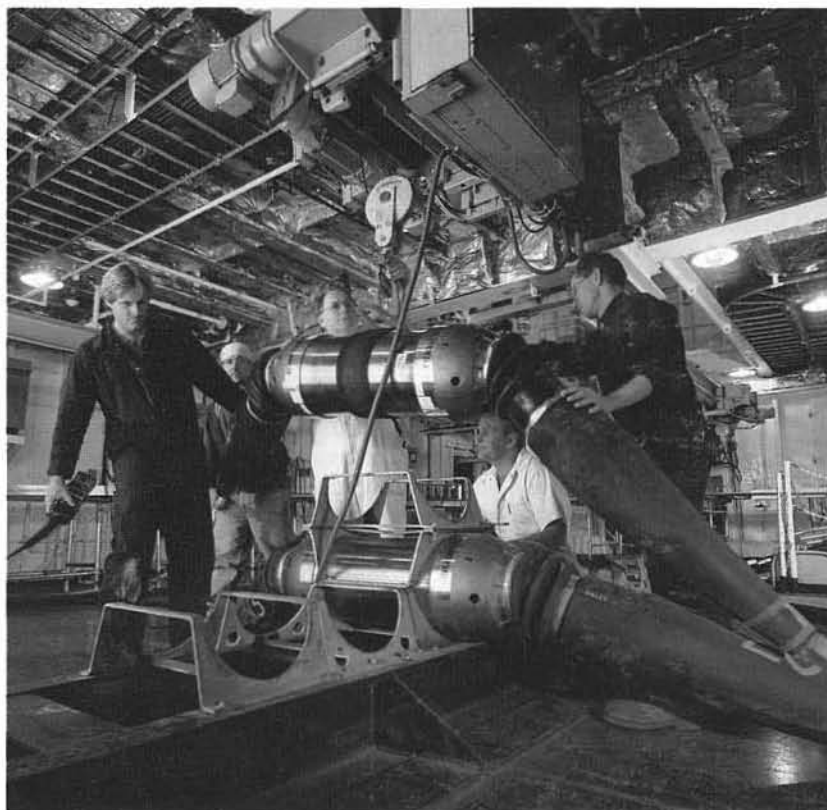
A natural "automatic gain control" is accomplished by designing the small signal gain of the amplifier to be larger than the attenuation in the cable section. Thus, if for some reason the power should drop in any particular section of cable, the following amplifier will see a smaller input power, resulting in an increase in gain so as to establish proper operating power in the rest of the optical path. The real challenge is to equalize the power over a wide optical bandwidth to allow for many WDM channels. Here we are not as fortunate as with the total
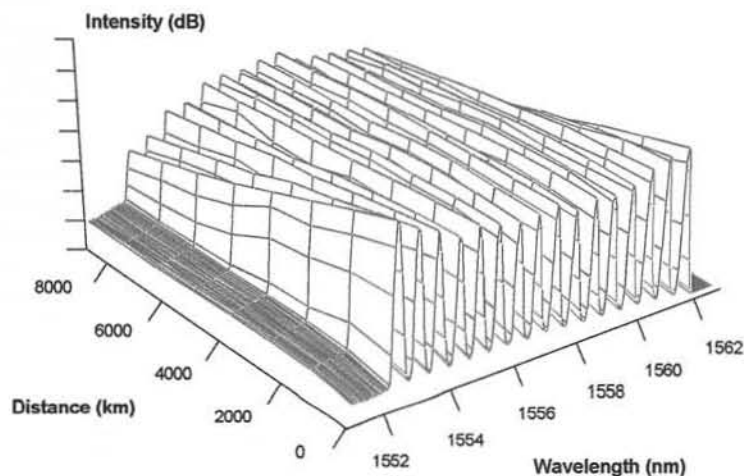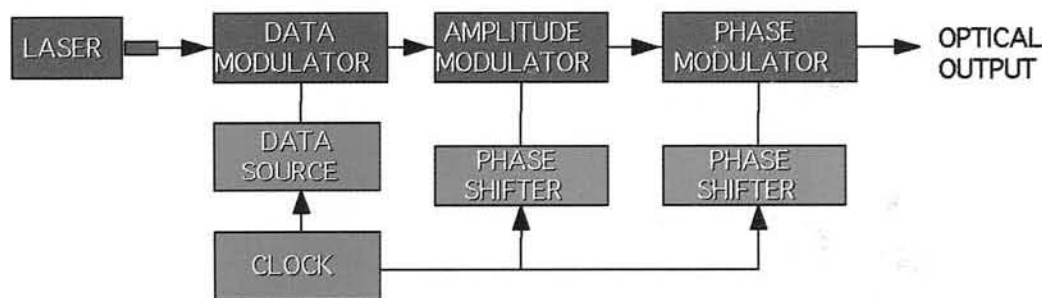

Figure 4. 3D plot of a WDM optical spectra recorded as a function of transmission distance.
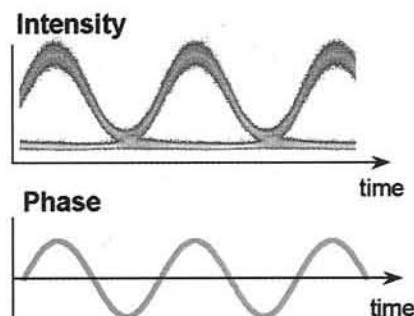
Figure 5. Chirped Return-to-Zero transmitter and waveforms.

power control given by the EDFA gain compression. Most of the gain equalization is accomplished using passive filters placed along the length of the amplifier chain. To a lesser degree, spectral hole burning in the EDFA aids in equalizing the channel-to-channel power variations (Figure 4).

Transmitting bits across the ocean

Although undersea lightwave systems are at the cutting edge of telecommunication technology, the basic signaling format is quite simple. Binary ones and zeros are sent by the presence or the absence of light pulses, much like one would use a flashlight with an on/off switch to convey a message in Morse Code. Instead of long and short pulses (dots and dashes), we use precisely timed flashes of light (on and off) to represent binary data. Instead of a flashlight, modern lightwave systems use a laser which has been turned on and off by an electro-optic modulator so that its intensity can be detected directly. The "hi-tech" aspect is that hundreds of billions of these pulses are transmitted per second through a single optical path that is megameters in length. One of the key challenges of system design is to transmit a pulse shape that will survive the long transmission distance in the presence of dispersion, fiber nonlinearity, and the added optical noise from the amplifiers.

Chromatic dispersion and the strength of the nonlinear index of the transmission fiber limit the system's performance for both a single channel and WDM transmission. The important manifestations of the fiber's nonlinear index include self phase modulation, four wave mixing and cross phase modulation. Since the strength of optical nonlinearity on a local level is quite small, the deleterious effects of the nonlinear index occur over many tens to hundreds of kilometers. This means that the nonlinear interaction lengths are long and that the local chromatic dispersion (which can be quite large) is an important factor in the system's performance. When the system is operated at the fiber's zero dispersion wavelength, the data signals and the amplifier noise (with wavelengths similar to the signals) travel at similar velocities. Under these conditions, the waves have a long interaction length and can mix together. Chromatic dispersion causes different wavelengths to travel at different group velocities in single-mode transmission fiber. Chromatic dispersion can reduce phase matching, or the propagation distance over which closely spaced wavelengths overlap, as well as the amount of interaction through the nonlinear index in the fiber. Thus, in a long undersea system, the nonlinear behavior can be managed by tailoring the dispersion accumulation so that the phase-matching lengths are short, and the end-to-end dispersion is small. This technique, known as *dispersion mapping*,[4] amounts to constructing the amplifier chain using optical fibers with opposite signs of dispersion.

Transmission formats

A robust transmission format that can propagate in the presence of dispersion and fiber nonlinearity is the chirped return-to-zero (CRZ) pulse shape. The CRZ pulse is formed by first modulating a cw laser with a high-speed non-return-to-zero (NRZ) data waveform (Figure 5). The NRZ waveform is then re-modulated with a sinusoidal amplitude and sinusoidal optical phase to form the CRZ pulse.[5] The added bandwidth on the CRZ pulse, together with the large local dispersion in the amplifier chain, determine the temporal, and hence the nonlinear evolution of the pulse. CRZ pulses in a single WDM channel periodically expand and contract as they traverse the different signs of local dispersion of the dispersion map. A single pulse might spread by several bit periods, making the actual data pattern seem to "disappear" at certain points in the system. The dispersion map for a transmission line is designed so that the pulses will have minimum temporal distortion at the receive terminal.

Many in the optics and physics communities question whether optical solitons are used in undersea cable systems. The optical soliton is another pulse waveform

that has been widely studied for long-distance data transmission. There was an active debate in the early 1990s between using NRZ or solitons for the first single channel EDFA based transmission systems. NRZ had the advantage of compatibility with existing systems and solitons were thought to have the advantage of higher single channel bit rates. It was decided that the first systems would use the NRZ format and that subsequent systems would use the "higher" capacity format. When WDM techniques became available, new dispersion maps were invented that strongly reduced four-wave mixing between NRZ channels, thus eliminating one of the big advantages of solitons. This made adding NRZ wavelength channels the preferred method for greatly increasing capacity, rather than making incremental improvements by increasing the bit rate per channel.

In the intervening years a few events changed the debate. Improved understanding of the basic physics of optical propagation has driven the evolution of both the NRZ and soliton transmission formats. The NRZ format has evolved into CRZ, and the soliton community has adapted dispersion mapping techniques to create "dispersion managed solitons." For 10 Gb/s WDM, the CRZ format has proved superior to solitons since it is much less limited by the fiber's dispersion slope. Today, the NRZ/soliton debate has changed to a question of, on the one hand, purposely using the fiber's nonlinearity to help guide data pulses, or on the other hand, to engineer out the system's nonlinear behavior and operate the system in a quasi-linear region. Clearly, designers working at multiples of 10 Gb/s have chosen the quasi-linear approach of managing the fiber's nonlinearity. Undoubtedly, the debate will be renewed when engineers are challenged with system designs based on 40 Gb/s and 160 Gb/s channel modulation rates.

Looking forward
By using more optical bandwidth and by using it more efficiently, the capacity of undersea fiberoptic systems will increase. The ultimate digital capacity that can be "fit" into the conventional pass-band of an EDFA depends on how efficiently this bandwidth can be used for data transmission. Based on a spectral efficiency of 0.5 bits/sec/Hz, the upper limit for C-Band capacity is about 2.5 Tb/s on a single fiber (where spectral efficiency is the system's average digital capacity divided by the average optical bandwidth of the system). Total system capacity can also be improved by increasing the number of optical fibers in the cable, but this presents an engineering challenge. The optical amplifiers must be more efficient in physical space given the limited amount of space in the pressure vessels, and their power requirements would need to decrease, given the limits of electrical power transmission in the cable.

The ultimate capacity of a transoceanic system can be estimated based on the bandwidth/spectral efficiency. The low attenuation window of typical telecommunications grade optical fibers is about 120 nm wide and extends from approximately 1500 nm to 1620 nm, corresponding to ~ 15 THz. Thus, the potential capacity of a transoceanic system is about 7.5 Tb/s. To take advantage of this capacity, wideband optical amplifiers are needed as well as wideband transmission fibers that have a "flattened" chromatic dispersion characteristic.

Erbium amplifiers can cover about two-thirds of this bandwidth by using both the C-band, and the newer "long" wavelength band (or L-Band) in the wavelength range of about 1570 nm to 1610 nm. The leading optical amplifier candidate for the remaining short wavelength band (S-band) is stimulated Raman gain, which would be accomplished by pumping the transmission fiber at ~1430 nm.

Recently, fibers that extend the concept of dispersion mapping by alternating both the sign and the slope of the dispersion have been reported. The resulting fiber spans have a relatively constant dispersion value over a broad bandwidth. Ultimately, one could envision using the entire pass-band of the transmission fiber from 1300 nm to 1700 nm, corresponding to 55 THz. This would pose many challenges to fiber and system designers. For example, a very broadband optical amplifier (or combination of amplifiers) would be needed, and the added attenuation of the fiber at the shorter wavelengths would decrease the signal-to-noise ratios for WDM channels in that region.

We have come a long way since the 1980s and the first undersea fiberoptic cables that revolutionized international telecommunications. Optical fiber cable networks now provide the bulk of the long-haul telecommunications for voice and data on both land and across seas. Today, transoceanic cable networks are being built with multi-terabit capacities. Ultimately, another order of magnitude increase in the data transmission capacity of single-mode fiber will occur given wider bandwidth amplifiers and improvements in spectral efficiency. These improvements will foster unprecedented capacity improvements for international telecommunications.

References
1. Bern Dibner, *The Atlantic Cable* (Burndy Library, Norwalk, CT, 1959).
2. R.D. Ehrbar, "Undersea Cables for Telephony," Chapter 1 in *Undersea Lightwave Communications*, Peter K. Runge and Patrick R. Trischitta, eds. IEEE Press 1986.
3. P. Trischitta, *et al.*, "The TAT-12/13 Cable Network," *IEEE Communications Magazine*, **34**, 24, No. 2, February 1996.
4. F. Forghieri, *et al.*, "Fiber Nonlinearities and Their Impact on Transmission Systems," Chapter 8 in *Optical Fiber Telecommunications IIIA*, Ivan P. Kaminow and Thomas L. Koch, eds., Academic Press 1997.
5. Neal S. Bergano, *et al.*, "320 Gb/s WDM transmission (64x5 Gb/s) over 7,200 km using large mode fiber spans and chirped return-to-zero signals," OFC'98, paper PD12, San Jose, CA, Feb. 1998.

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