The threat of a capacity crunch in the worldwide fiber communication system, as pump sources for Raman amplification, has attracted new interest.
The threat of a capacity crunch in the worldwide fiber communications system, and the availability of inexpensive, high-power diodes as pump sources for Raman amplification, has attracted new interest in the virtues of a decades-old technology.
he exponentially growing demand for higher data transmission capacity—driven by expanding Internet traffic, the “Internet of Things,” on-demand video and the rise of cloud-based services—is placing new burdens on the optical transmission infrastructure. Optical fibers form the linchpin of the system across many applications (no more transoceanic voice calls are done via satellite today) and through much of the global network architecture—for example, backhauling traffic from cell towers is achieved with high-capacity fiber links. The development of exabyte-scale data centers has even made geography irrelevant; the content of any website may be stored in another country or continent, requiring ultra-long-haul, ultra-high-capacity connectivity.

Raman optical amplification could open further, new optical windows within the huge fiber spectrum for more wavelengths and higher line capacity.

This situation has confronted society with a looming “capacity crunch,” as the demand for ever-greater data transfer increasingly approaches the spectral efficiency limits of the current fiber system. Researchers are busily engaged in devising solutions, which in the long term could require significant and potentially costly reconfiguring of the entire fiber infrastructure (see OPN, March 2015, p. 28). But in the short and intermediate term, society needs a way to expand the throughput of the current fiber system at reasonable cost, to navigate the difficult road to that longer-term solution.

One such “new” near-term approach has actually been around for decades: Raman optical amplification. While largely sidelined with the advent of erbium-doped fiber amplifiers (EDFAs), Raman amplifiers are again attracting attention as one tool for staving off optical network capacity shortages in the next several years—at a reasonable cost. And these systems are being deployed in both terrestrial and undersea cable systems.

The fiber capacity challenge

Up until now, continual development of new transmission technologies has allowed optical network capacity (the total amount of data, in Gbit/s, that can be sent along an optical fiber) to keep pace with demand—at ever-lower costs per bit. Higher bit rates per wavelength, digital coherent detection, better forward error correction, and dense wavelength division multiplexing (DWDM) have all helped boost capacity. Network robustness has also benefited from flexible optical wavelength switching (see OPN, March 2015, p. 36) and improvements in optical reach (the distance an optical signal can travel before it needs to be regenerated in the electrical domain before conversion back to the optical domain).

The technology growth has led to a self-reinforcing cycle: increased data transmission demand prompts new approaches to boost network capacity, leading to a drop in the cost per bit of data transmission, which spurs new capacity-intensive applications that lead to further transmission demand increases. Coping with this cycle will require technical solutions that go beyond today’s standard of 100-Gbit/s optical channels built upon polarization multiplexing quadrature phase shift keying (PM-QPSK) modulation, coherent detection and digital signal processing (DSP), which can achieve a line capacity of about 9 Tbit/s over 2,000 km in a single fiber.

Surpassing that current technology standard calls for more sophisticated modulation formats, such as 16-state quadrature amplitude modulation (16QAM), to increase spectral efficiency (equal to the bit rate divided by channel spacing). This modulation format forms the foundation for 200-Gbit/s carriers, with optical channels at 400-Gbit/s or higher rates based on the combination of two or more tightly spaced 200-Gbit/s carriers. This approach can boost line capacity as high as 23 Tbit/s within the optical spectrum offered by EDFAs, today’s most common optical amplification technology.

That increase in spectral efficiency, however, faces a fundamental limitation: the higher the spectral efficiency, the higher the optical signal-to-noise ratio (OSNR) requirement at the
output of the optical path. A 16QAM link operating at 200 Gbit/s per carrier requires about 7- to 7.5-dB higher OSNR than a QPSK channel at 100 Gbit/s per carrier—a more than fivefold increase in linear units. And, while boosting signal power can, in theory, improve OSNR, fiber nonlinearities will cap the per-channel power that can be launched into the fiber spans.

Increasing fiber capacity without compromising all-optical reach requires new approaches. Space division multiplexing (SDM), based on multicore or multimode fibers, has been proposed, but SDM would require redeveloping the entire ecosystem of passive and active optical components, which makes it a long-term solution at best. And SDM solutions can’t use the two billion kilometers of optical fibers that have already been deployed worldwide.

**Raman amplification: For greater capacity...**

Raman optical amplification offers one simple, field-proven way to resolve the capacity dilemma, both for existing fiber plant and in the new fiber infrastructures to be deployed in the coming decades. Its advantages rest on some significant potential spectral benefits relative to EDFAs.

Typically, the usable spectrum for EDFAs is 36 nm. By contrast, Raman amplifiers accommodating 240 wavelengths spaced at 50 GHz, in a much wider 100-nm spectrum (ranging from 1,520 to 1,620 nm), have been in commercial use since 2004. Moreover, Raman optical amplification could open further, new optical windows within the huge fiber spectrum for more wavelengths and higher line capacity—for example, Raman fiber amplifiers operating in the so-called S band, at 1,460 to 1,530 nm, were demonstrated 15 years ago. The sum of these optical spectra could reach 200 nm.

The optical frequency of the Raman scattered photon (or, equivalently, of the Raman gain region) is determined by the optical pump frequency and material. Inside silica single-mode fibers, the frequency shift between the pump and scattered photons is about 13.2 THz downwards, corresponding to about 100 nm above the pump wavelength in the 1,550-nm telecommunications window. The Raman gain spectrum bandwidth is close to 3 THz or 25 nm (at the –2-dB point) and can

---

**What is Raman amplification?**

Raman amplification is based on the nonlinear optical effect of stimulated Raman scattering, and uses the silica in the fiber itself, rather than rare-earth doping, for laser gain.

When a photon from an intense optical pump [1] is launched into silica fiber and interacts with a molecule [2] in the fiber, the excited silica molecule [3] usually relaxes immediately to its initial state and emits a scattered photon of the same energy (that is, the same optical frequency and wavelength) as the incident pump photon. This is known as elastic, or Rayleigh, scattering.

In some cases, however, the emitted photon, called a Stokes photon [4, 7], carries a lower energy (lower frequency and longer wavelength) than the incident pump light \( hν_s < hν_p \), with the remainder of the initial pump photon energy carried off as vibrational energy (phonons) in the crystal lattice [5, 8]. This inelastic case is known as Stokes-Raman scattering.

Raman amplification of an optical signal occurs when the signal’s frequency falls within the frequency band of Stokes photons scattered from the pump source (known as the Raman spectrum). The input signal photon \([6, 9]\) triggers the stimulated emission of a photon at the signal wavelength, which is in phase with, and propagates in the same direction as, the original signal photon, and so leads to Raman gain.

Because of the vibrational modes specific to silica molecules, the maximum Raman gain commonly occurs at a frequency difference of 13.2 THz between the pump and signal waves, corresponding to 100-nm wavelength differences in the 1,550-nm region, where fiber attenuation is minimal.
Raman amplification can also extend the potential reach of optical fiber transmission relative to EDFA.

be expanded by combining optical pumps at different wavelengths.

... And better reach
Raman amplification can also extend the potential reach of optical fiber transmission relative to EDFAs. That’s because, in a Raman-powered optical network, the line fiber is not only a transmission medium that attenuates the optical signals, but also a gain medium, because of distributed Raman amplification occurring inside the fiber itself. That, in turn, reduces the nonlinear penalty that can degrade the signal integrity.

Most nonlinear effects in silica optical fiber are caused by the optical Kerr effect, in which the refractive index of the optical waveguide changes as the instantaneous optical intensity increases. The higher the signal power, the higher the nonlinearities and the subsequent distortions that are experienced by the optical signals. Nonlinearities impose an upper limit on the per-channel power that can be launched into the optical fiber. And the higher channel rates and multilevel modulation formats found in optical transmission systems of 100-Gbit/s and higher capacity have made those systems more sensitive to fiber nonlinearities than those based on direct detection at 10 Gbit/s.

Because of these effects, optical networks based on EDFAs have limited transmission reach for 16QAM signals. Granted, the EDFAs themselves have good optical noise performance, with a relatively low level of optical noise generated by the amplifiers. But the level of optical noise is directly proportional to the optical gain and, hence, to the loss of the fiber span to be compensated for. Simple analytical calculation shows that the accumulated noise power at the output of a repeatered link of a given length is smaller with a larger number of amplifiers, each exhibiting a smaller gain, than for a link made of longer spans, with fewer amplifiers each having higher gain.

This is why transoceanic links use short spans, at low span loss, to maintain a high OSNR at the output end, even after a 10,000-km transmission distance. Terrestrial fiber links must be designed

EDFA versus Raman
In a typical system with "lumped" erbium-doped fiber amplifiers (EDFAs), the amplifier delivers an instantaneous power boost, and signal attenuates over the course of the fiber to the next amplifier (top). In a distributed Raman system, the line fiber is not only a transmission medium that attenuates the optical signals, but also a gain medium because of distributed Raman amplification along the length of the fiber itself. As a result, Raman systems have a lower peak-to-peak power excursion along the optical path, and lower nonlinear distortions and noise accumulation.

Illustration by Phil Saunders/Adapted from Xtera Communications Inc.
with span lengths imposed by the availability of intermediate sites to house the in-line amplifiers, which results in longer (and nonuniform) span lengths compared with submarine links.

All of this limits the practical reach for 16QAM signals over EDFA links to about 600 km. Heroic experiments with state-of-the-art fibers (exhibiting ultra-low loss and very large effective area) have been reported over longer distances, but these results don’t map to what can be achieved in existing terrestrial fiber networks.

A distributed Raman amplifier, by contrast, can be thought as an additional line amplifier inside the fiber span. Thus, distributed Raman amplification is analogous to shortening the span length (that is, the length of the span found in an EDFA system becomes two spans with distributed Raman amplification), or to reducing the effective span loss because part of the line fiber has less signal attenuation due to distributed amplification.

In addition, backward Raman pumping—that is, systems in which the Raman pump counter-propagates with respect to the optical signals—adds almost no nonlinear transmission penalties, since the gain occurs at low signal power. As a result, backward Raman amplification with about 10-dB gain can improve OSNR by about 4.7 dB relative to EDFA-only amplification. That’s a threefold improvement in linear units, and means that optical signals with the same intensity can propagate over three times as many spans without regeneration. Systems combining forward and backward Raman can improve OSNR even more, in the range of 8.5 dB or higher, a sevenfold gain in linear terms.

How might this play out in real-world systems? Field trials conducted in 2013 by NEC and Xtera, in the Verizon U.S. network, demonstrated that Raman line equipment enables 16QAM, 400-Gbit/s transmission across more than 2,000 km on an aged, high-loss fiber plant in a real network environment.

**Implementing Raman amplification**

How can Raman amplification be implemented in an existing fiber network? Three approaches are possible:

**Distributed.**

Building Raman amplifiers can be as simple as coupling wavelength- and polarization-multiplexed pump power into the line fiber. In a backward Raman implementation, Raman pumps are launched into the preceding fiber span in a direction counter to the direction of transmission for optical channels. In the forward Raman implementation,
the Raman pumps are launched from the repeater site into the following fiber span in the same direction as the optical channels.

Lumped.
Raman amplifiers can be also designed to provide discrete amplification, achieved using a coiled length of specialty fiber inside the amplification site.

Hybrid.
Finally, hybrid Raman/EDFA amplifiers can be implemented. In this case, however, only the OSNR and reach benefits of Raman will be available. The capacity benefits will be lacking, as the EDFA part of the hybrid amplifier will constitute a bottleneck constraining the spectrum to less than 40-nm width.

In any of these implementations, control of the amplifier will require monitoring capabilities and dynamic control loops specific to this technology. A Raman controller differs from an EDFA controller, because of the different physics involved and the more flexible behavior of the Raman amplifiers (for instance, the gain spectrum can be dynamically shaped via pump-power-per-wavelength adjustments). The typical pump power launched into the line fiber for distributed Raman amplification is around 1 W, which requires standards-compliant systems to ensure eye safety in the event of a line cut.

Raman amplifiers can operate with standard optical connectors at the optical distribution frame (ODF) level or in the line. The most robust solution is to use connectors with expanded cores that have much higher optical damage thresholds.

Properly designed Raman amplifiers are invisible to operators in their networks. In addition, Raman systems can respond to significant changes in optical attenuation in the fiber plant over the entire system lifetime due to, for instance, additional loss following cable cuts and repairs. Raman networks can also quickly adapt to any sudden change in the number of WDM channels, in the event of, for example, fiber cuts before the nodes or rerouting of a group of channels to another path in the network.

Raman’s continuing evolution
While compact, efficient EDFAs surpassed Raman technology at the end of the 1980s, Raman came back on stage ten years
later—not because of any changes in physical principles or performance, but because of evolution in the technology required to build Raman amplifiers. Most fundamentally, the development and commercialization of practical, high-power laser diodes greatly reduced the cost of delivering the amount of pump power required for Raman gain in optical networks.

Raman amplification started to be used in optical transmission systems at the end of the 1990s for unrepeatered submarine cable systems, where placing intermediate equipment was not an option (that is, where there was no span of cable accessible on land between the two end points) or when the traffic demand could not justify the cost of installing submerged repeaters. Specific terminal equipment, featuring Raman pump modules, enabled the deployment of unrepeatered links with a length close to 350 km for 622-Mbit/s, 2.5-Gbit/s or 10-Gbit/s channel rates.

Over time, and with the introduction of 100-Gbit/s channel rates at the beginning of this decade, Raman amplification has become more widespread in terrestrial networks. With well-established EDFA technology, only easy links with modest span lengths and limited end-to-end reach could effectively be deployed in the field over existing fiber plants. Spans exceeding 100 to 120 km, as found in many vast or emerging countries, or end-to-end optical paths longer than 1,500 to 2,000 km, not uncommon for data center interconnects, require Raman amplification to offer a lower cost per transported bit. With no Raman amplification, such optical links would need to make use of intermediate regeneration sites that require large capital and operational expenditures, not to mention the high incremental cost when new capacity is added.

This rationale is especially true for 200-Gbit/s and 16QAM channels and superchannel approaches based on the concatenation of several 200-Gbit/s carriers. The higher sensitivity of these channels to optical noise and fiber nonlinearities will limit them to metropolitan or regional applications in an EDFA-based system. For long spans and long-haul transport over lossy fibers, Raman amplification offers a practical answer for multi-terabit transmission over existing fiber infrastructure.

This applies to both terrestrial and submerged amplifiers. An improved electrical design of long-haul repeatered submarine cable systems allowed deployment of the first Raman-based optical repeaters for submarine cable systems in 2015. As with their terrestrial counterparts, these new submerged amplifiers offer wider spectrum, better noise performance and longer spacing between repeaters. With line technologies common to both dry and wet parts of the networks, the demarcation points traditionally found in cable landing stations can be removed, enabling unified optical networks with end-to-end, seamless all-optical connectivity between data centers—even in the presence of vast stretches of water in between.

With the potential to multiply the spectrum offered by EDFA systems by a factor of three, and to transport high channel rates over longer distances, Raman amplification represents a critical tool for solving the capacity-cost quandary for networks operators—and one that, in contrast to SDM, uses the existing ecosystem of fiber assets and optical components. That makes it an effective, efficient solution in both the short and intermediate term.

Bertrand Clesca (Bertrand.Clesca@xtera.com), Herve Fevrier and Wayne Pelouch are with Xtera Communications Inc., Allen, Tex., USA.

An improved electrical design of long-haul repeatered subsea cables allowed deployment of the first Raman-based optical repeaters for submarine cable systems in 2015.

References and Resources

- D. Chang et al. "150 x 120 Gb/s field trial over 1,504 km using all-distributed Raman amplification," OFC 2014, San Francisco, USA, Tu2B.2.