INVITED PAPER

Challenges of Raman Amplification

When optical pump energy is added along with signals in ordinary optical fibers, optical amplification can take place, providing low-noise, flat, wideband signal gain.

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ABSTRACT | Raman amplifiers are often regarded as a typical example of technologies rapidly developed in the midst of turmoil created by the so-called wavelength division multiplexing (WDM) bubble. Indeed, Raman amplifiers turned out to be technically very attractive in all the aspects of capacity, reach, and bit rate. Even though Raman amplifiers are actually being deployed into systems in commercial service, the practical issues, such as cost, reliability and safety, are yet to be further discussed, particularly for the configuration of distributed amplification. After summarizing the advantages of Raman amplification and reviewing pump laser technologies, this paper will highlight ongoing efforts on practical issues, which include reliability and safety issues of fiber under high-power operations. Finally, it is concluded that by overcoming the above-mentioned practical issues, Raman amplification will stay as a key technology for future optical communications because of its compelling unique advantages.

KEYWORDS | Fiber fuse; 14XX-nm pump lasers; optical amplifier; optical damage; Raman amplification; Raman amplifier; Raman scattering; wavelength division multiplexing (WDM); wavelength division multiplexing (WDM) pumping

I. INTRODUCTION

Regardless of the reckless bursting of the so-called wavelength division multiplexing (WDM) bubble in 2001, Internet traffic has ever been increasing and this trend seems to stay unchanged for the foreseeable future. Behind the constant increase of Internet traffic, various applications have emerged one after another, exploiting higher bandwidth per user. One of such applications in the past was the widespread use of World Wide Web technologies. Streaming of music and/or motion picture content may currently be such an application. It is also important to observe that, soon after the WDM bubble burst, the FTTH boom came along in Japan. FTTH is the abbreviation for "fiber-to-the-home," the most powerful technology for Internet broadband access at home. Fig. 1 shows how the number of broadband access subscribers in Japan has been increasing in recent years. Although the data is uniquely from Japan, the global popularization of broadband access will be inevitable soon or in the near future. In conjunction with the widespread use of FTTH technologies, real-time transmission of superhigh-definition images will be the next widespread application to utilize abundant bandwidth in the near future. In order to transmit massive real-time images, each user has to be guaranteed to have more than a few gigabits per second end-to-end connectivity, which is many orders of magnitude higher than the present average connectivity per Internet user. As the connectivity increases, new uses of the network, using new technologies, such as GRID computing and/or P2P technologies, will appear. And such new technologies inviting new emerging applications will in turn increase the demand for even higher bandwidths.

There are plenty of ways in different network layers, ranging from optimizing the network architecture to the use of better fiber links, to enhance the connectivity. In any of these approaches, the portion of the data staying in the optical rather than the electric domain would increase in the future networks with higher data capacity and efficiency. The more the data is in the optical domain, the more the optical transmission performance of the system has to be well maintained. The performance of the optical transmission is mostly determined by optical transmission links consisting of optical data transmitters and receivers, optical fiber cables, optical switches/couplers, and optical amplifiers. This paper focuses on optical fiber Raman amplifiers, which are an emerging technology and in fact being gradually deployed for the commercial services.

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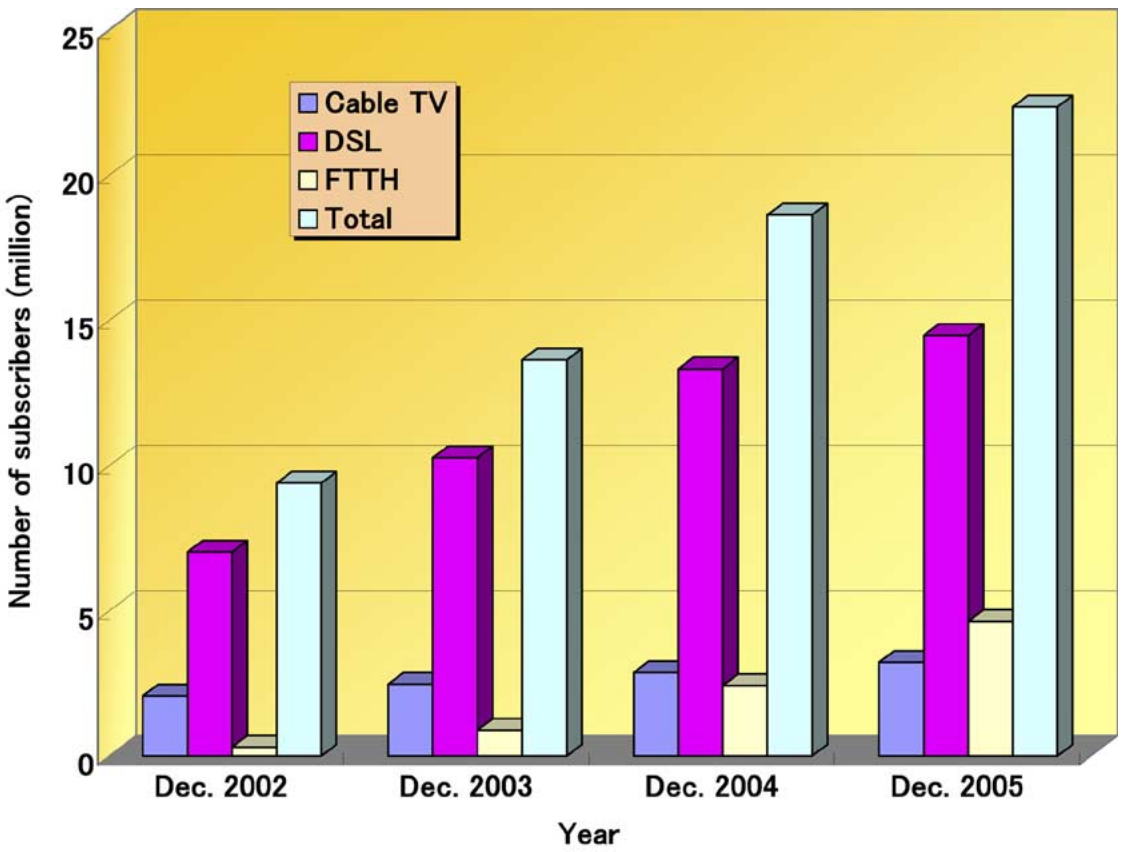


Fig. 1. *Transition of the number of broadband access subscribers in Japan (source: http://www.soumu.go.jp/s-news/2006/060303_8.html).*

Raman amplifiers are superior to any other alternatives for optical amplification in terms of high signal transmission performance, as will be seen in the following sections. Although Raman amplifiers have superior potential, the state-of-the-art optical amplifiers are erbium-doped fiber amplifiers (EDFAs), which have been widely used in the actual optical transmission systems now in service. EDFAs are of low noise, compact, highly efficient with high gain, and capable of amplifying multichannel signals on different wavelengths at a time, and hence quite economical for WDM transmissions. Another alternative of optical amplification is the semiconductor optical amplifier (SOA), which is nominally an optical amplifier device with an active waveguide integrated onto a compound semiconductor. SOA is superior in the sense of high integration and additional functionality such as wavelength conversion and all-optical regeneration.

In this paper, we will see why Raman amplifiers have uniquely superior transmission performance and review high-power pump laser technologies as a key technology for Raman amplifiers. And finally, we will discuss some issues on handling high operating power in order for Raman amplifiers to be widely used exploiting their superior performance.

II. RAMAN AMPLIFICATION IN OPTICAL FIBER

In general, the fundamental mechanism of an optical amplifier is through stimulated emission of photons [1]. There are many types of optical amplifiers, such as EDFA, SOA, and Raman amplifiers. They are based on different materials and different processes of stimulated emission. EDFAs use the transition between a pair of energy levels of erbium ions doped in silica glass fiber, where the difference of energy levels coincides with the optical frequency of the signal to be amplified. SOAs use the electron–hole recombination for optical amplification, and the energy bandgap of the semiconductor corresponds to the optical signal frequency. These types of amplifiers have two "real" energy states in which electrons can stay for a well-defined duration. On the other hand, Raman amplifiers use stimulated Raman scattering of silica glass fiber, which is inelastic scattering of a photon with a molecule. The interaction between the incident photon and molecule will cause the molecule to vibrate, resulting in the frequency downshift or the Stokes shift of the photon for the sake of energy conservation. This process can be described with regard to quantum mechanics as depicted in Fig. 2.

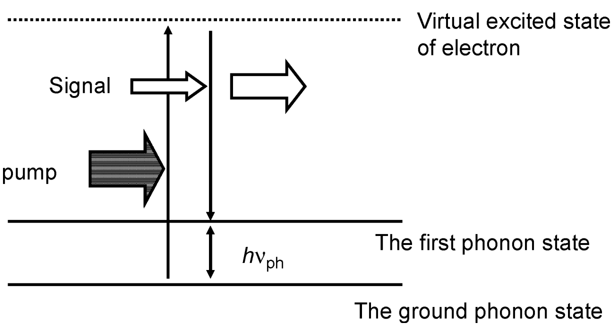


Fig. 2. *Quantum mechanical description of stimulated Raman scattering process.*

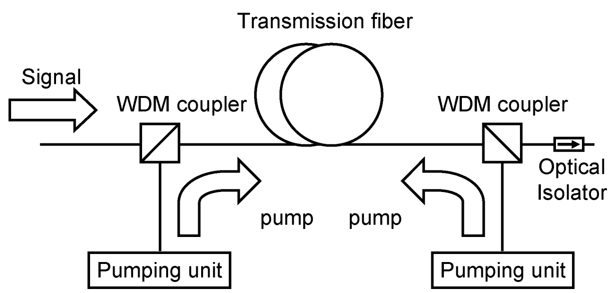


Fig. 3. *General scheme of fiber Raman amplifiers.*

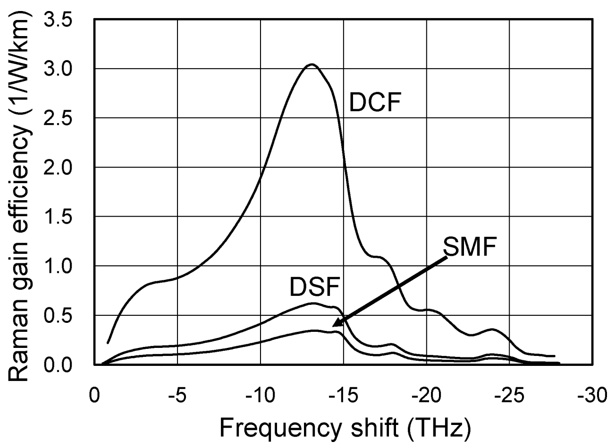


Fig. 4. *Typical Raman gain efficiency spectra for standard single mode fiber (SMF), dispersion shifted fiber (DSF), and dispersion compensating fiber (DCF).*

Absorbing the incident photon, an electron belonging to the ground state of molecule is excited to a "virtual" excited state. "Virtual" means that the electron cannot be stable in this state for a definite duration ,but it can dwell there for a very short time as long as Heisenberg's uncertainty relation allows. And the Raman scattering completes when the excited electron deexcites to the first molecule vibration state, emitting a Stokes photon. The stimulated emission is possible even from the virtual upper state to the first molecule vibration state. Therefore, if the incident optical signal is at a frequency shifted by Stokes frequency from the pump, the stimulated emission of the optical signal can occur. This process is the mechanism of Raman amplifiers. One important implication here is that, unlike other amplifiers, Raman amplification is possible for signals at any wavelength provided that the frequency of pump is higher than that of signal by the Stokes shift.

In order to construct a Raman amplifier using optical fiber as gain medium, pump and signal light waves have to be jointly launched into the same fiber for stimulated Raman scattering. As stimulated Raman scattering occurs almost uniformly for all the orientations between the pump and signal propagation direction, fiber Raman amplifiers can work both for the counterpropagating and copropagating pump with respect to the signal. Therefore, the general scheme of fiber Raman amplifiers becomes what appears in Fig. 3

For telecommunication purposes, signal wavelengths are usually around 1550 nm. And the Stokes shift of silica glass fiber is approximately 13.2 THz, corresponding to 100 nm in the telecom window. Therefore, in order to amplify the 1550-nm signal, the wavelength of the pump light has to be around 1450 nm. Fig. 4 shows the typical Raman gain spectra for typical fibers. Due to amorphous nature of glass, the Raman gain spectra have fairly broad profile, being suitable for WDM applications. In spite of different designs, the profiles of gain spectra of these fibers resemble each other. The slight difference of the profile derives mostly from the different concentrations of germanium doped in the core of the fiber, while the magnitude is roughly in inverse proportion to the effective area of the fiber.

The gain efficiency in the unit of 1 /W/km represents the rate at which the signal grows per infinitesimal fiber length for 1 W of pump power. Therefore, the growth of signal level is exponential. And the total signal gain for a given length of fiber can be calculated. From Fig. 4, one can see that the peak of the gain spectra for SMF is approximately 0.33 /W/km. If the attenuation of SMF were neglected for simplicity, the maximum signal gain would be 14 dB for a 10-km SMF with a launch pump power of 1 W, though in an actual case, fiber attenuation at both signal and pump wavelengths causes the gain to be much smaller. One of the drawbacks of Raman amplifiers is their poor performance in terms of pump power efficiency compared to the EDFA with the same net gain. Poor efficiency and the lack of enough high-power pump lasers were the critical reasons why Raman amplifiers have not been widely used like widespread EDFAs.

In the following, we will discuss how the characteristic difference of Raman amplifiers leads to unique merits for

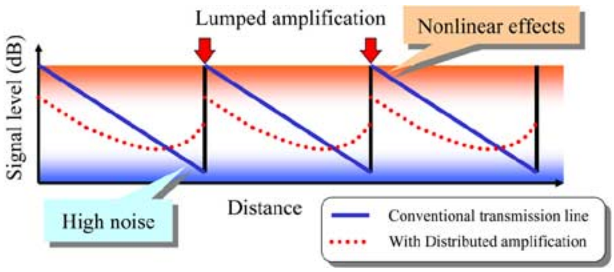


Fig. 5. ***Signal level diagram of typical transmission lines with and without distributed amplification.***

future high performance systems, aside from a shortcoming of efficiency. Also, a technique called WDM pumping will be introduced, and it will be explained how this technique overcomes the poor efficiency or the high pump power requirements in practice.

III. MERITS OF FIBER RAMAN AMPLIFIERS

One particular feature of fiber Raman amplifiers is that the gain medium is the conventional low-loss silica fibers, the same material as used for transmission line. This means that ordinary, transparent, passive optical fibers can be turned into an active, lossless, or even amplifying waveguide of optical signals by means of Raman amplification. Because of the "virtual" nature of the Raman process, the absence of pump does not mean the medium absorbing signal light, but simply a conventional low-loss fiber. Therefore, just introducing sufficient pump power into the fiber link, it becomes less lossy. Intuitively, we may imagine that the fiber link could be extended to the extent of additional Raman gain in the fiber, which is in fact the case for an application of "repeaterless" transmissions for undersea systems. But more generally speaking, lower loss of fiber leads to the smaller magnitude of the signal level excursion, as shown in Fig. 5 [2]. In the conventional EDFA repeater systems, the signal monotonically attenuates in the fiber span, which is amplified at a point of the EDFA location to recover the original level before entering the next fiber span. This is why EDFA is sometimes called a lumped amplifier, while Raman amplifiers are mostly used in a "distributed" configuration. A lumped Raman amplifier (LRA) is possible; however, distributed Raman amplifiers (DRAs) have many attractive features as follows. A simple design scheme of optical transmission systems can be perceived when we turn to the optimization of the signal level diagram as shown in Fig. 5. The transmission impairments are caused mostly by signal quality degradation due to optical nonlinearity in the transmission fiber and amplified spontaneous emission (ASE) noise entailed by optical amplifiers. In the presence of DRA, the magnitude of the signal level excursion is smaller than the case with EDFA only, which is advantageous from the aspect of system design, better avoiding both nonlinearity and degradation of OSNR due to ASE noise.

In addition to the above feature of DRA, it should also be mentioned that ASE noise in fiber Raman amplifiers is intrinsically low. This is because the very fast relaxation of the optical phonon does not allow the electrons to stay long in the lower state, and hence the inversion population is almost always complete. Also, in the thermal equilibrium, the noise figure could be as small as 3.1 dB which is very close to the so-called quantum limit (3 dB). It is noteworthy that this value, unlike EDFA, does seldom depend on the pump power. Raman amplifiers could work easily as the nearly ideal distributed amplifier [3].

Let us consider by taking an example why a distributed amplifier is so unique and outperforms EDFA only. In optically amplified systems, extra loss before an optical amplifier directly translates into decrease in OSNR. For example, if a DRA provided the attenuated optical signal with a 6-dB gain in front of an EDFA, the OSNR degradation would be reduced by 6 dB compared with the case without DRA. Of course, we must take into account that Raman amplification entails ASE noise. The amount of decrease in noise figure due to introducing distributed amplification is represented by the so-called effective noise figure. The effective noise figure of a DRA is defined as the noise figure that a lumped amplifier placed at the end of the transmission line would need to have in order to achieve the same OSNR achieved by the DRA if the DRA were not employed. If the effective noise figure is less than that of EDFAs, then the system would benefit from introducing a distributed amplification. By definition, the effective noise figure could be negative, while the noise figure of EDFAs cannot be less than 3 dB due to the quantum limit.

In typical terrestrial optical transmission systems, the fiber span length between EDFAs is usually 80–100 km, corresponding to the span loss of 20–30 dB. From the above argument with respect to Fig. 5, it would be ideal if the span loss is entirely compensated by DRA alone, to minimize the signal level excursion. However, a DRA having more than 20 dB gain in SMF is challenging because of two reasons: first, pump power necessary to achieve such a high gain in SMF is more than 1 W and is still challenging, even though we have very powerful state-of-the-art pump lasers, as we shall see below. Second, too much distributed gain results in undesirable effects called double Rayleigh backscattering, and thus deteriorate the signal quality [4]. Therefore, from both practical and theoretical aspects, DRAs and EDFAs should complement each other. And in fact many of the commercial systems using DRAs employ "hybrid" amplification, in which both DRA and EDFA are used. On the other hand, it should be pointed out that there have also been efforts to improve transmission fibers more suitable for Raman amplification, and in fact

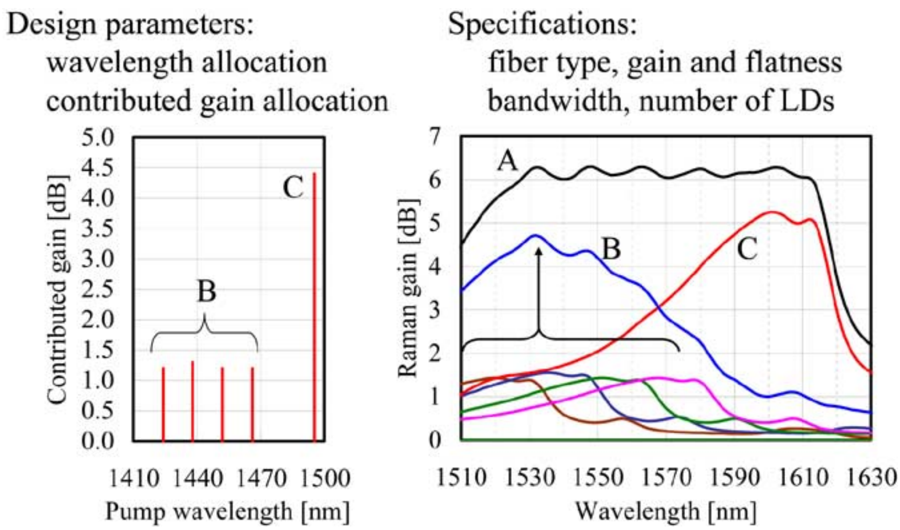


Fig. 6. ***Concept and design of WDM pumping for flat and broad Raman gain spectra. Curve A is the sum of curve B and C, whose corresponding pumps are labeled, respectively.***

that high-performance all-Raman amplified systems have been demonstrated using novel types of fibers [5].

Another unique merit of Raman amplifiers is gain at any wavelength by proper choice of pump wavelength. This is because the wavelength of the amplified signal is determined solely by the frequency difference between the pump frequency and the frequency of the optical phonon (Stokes frequency). Given a proper wavelength of pump lasers, Raman amplifiers could operate in a signal band outside the EDFA bands. In fact, LRAs operating in the *S*-band have been demonstrated in lab experiments [6]. Such application of Raman amplifiers will open a new transmission window in the future.

This feature is very useful even when a DRA operates in the EDFA bands. For WDM systems, the spectral profile of gain should be as flat as possible in order to equally amplify all the WDM channels. The gain profile of Raman amplifier, shown in Fig. 4, is approximately 15 nm wide in the EDFA bands. However, because the bandwidth of $C+L$-band is more than 80 nm, the flatness of Raman gain is not enough. In order to make Raman gain flat, a gain flattening filter could be used just as done in EDFAs. However, the use of such a component leads to lower efficiency and higher cost. Instead, utilizing the feature of gain at any wavelength, we could compose a flat Raman gain by simultaneously launching pumps at different wavelengths. The Raman gains created by the pumps at different wavelengths are slightly shifted from each other so as to partly overlap each other forming a composite gain. By properly choosing pump wavelengths and adjusting each pump power, the composite Raman gain can be very flat over a wide band. Because the Stokes shift is about 100 nm in the 1550-nm band, the composite gain could cover a nearly 100-nm signal band. It is noted that even EDFAs can not provide such a broad gain bandwidth; typical *C*- and *L*-band EDFAs have only 30–40-nm gain bandwidth, respectively. This technique is called WDM-pumping of the Raman amplifier. Fig. 6 illustrates the concept and design of WDM pumping. Each gain shape in frequency domain is identical but laterally shifted, and the magnitude is determined by the weighting factor corresponding to the path-averaged pump power.

The beauty of WDM pumping arises not only from the wideband gain flatness, but also from the fact that the output power necessary for each pump laser may be reasonably small as the total pump power is diversified. In fact, as we will see in the subsequent section, several 100–200-mW laser diodes would be fairly sufficient to realize a useful flat Raman gain for $C+L$-band. Furthermore, WDM pumping allows us to realize bandwidth upgradeability and robustness by redundancy as well as better thermal dissipation for higher efficiency and reliability. Likewise, WDM pumping mitigates poor efficiency of Raman amplification and helps Raman amplification to be sufficiently practical.

IV. PUMP LASER DIODES AS THE STATE-OF-THE-ART RAMAN TECHNOLOGIES

Since a DRA uses the deployed transmission fibers as gain medium, a DRA unit is usually a pumping unit without gain medium, and this is the reason why such a unit is often called a Raman pumping unit (RPU). Fig. 7 shows a schematic diagram and the photographic appearance of an RPU that is capable of amplifying $C+L$-band. RPU usually consists of pump lasers at 14XX nm, optical couplers to combine them, isolators, and a few monitor taps, as well as the WDM coupler for signal and pump. Depolarizers are necessary,

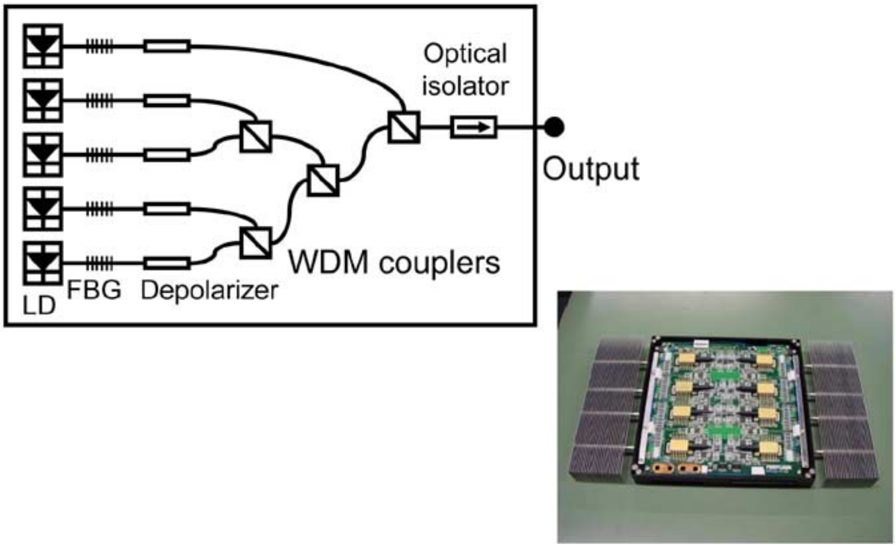


Fig. 7. *Schematic diagram and its photographic appearance of a $C + L$-band Raman pumping unit.*

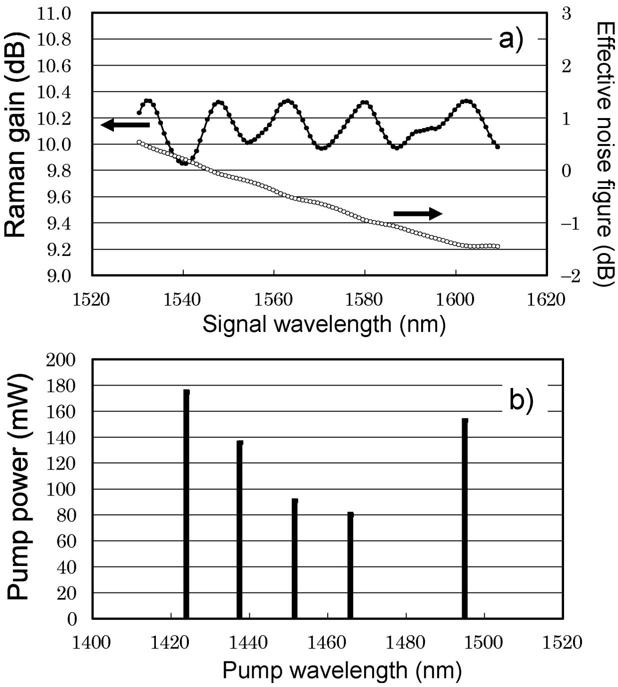


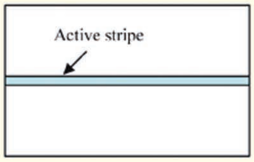
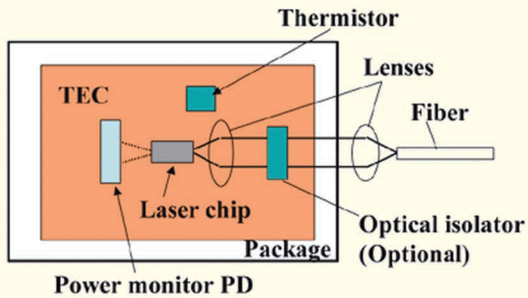
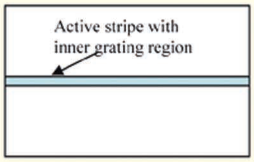
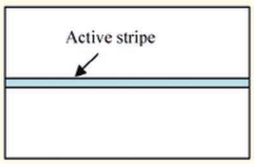
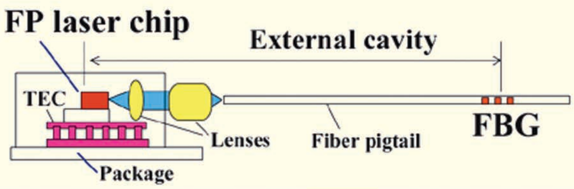
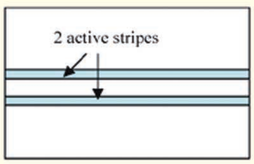
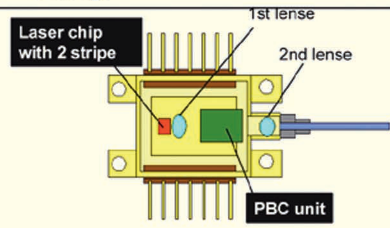
Fig. 8. *(a) Example of gain and effective noise figure spectrum along with (b) the launch pump power allocation for 80 km of standard SMF.*

when the pump is polarized, in order to suppress the polarization dependence of Raman amplification [7].

Fig. 8 shows an example of gain and effective noise figure spectra along with the launch pump power allocation for 80 km of standard SMF. Over the entire signal band, the effective noise figure is well below the 3-dB quantum limit and mostly negative, indicating the noise improvement due to DRA. However, the spectral shape of the noise figure is significantly tilted, and it tends to be worse at shorter wavelengths. This phenomenon mainly stems from pump-to-pump Raman interactions and/or thermal noise larger at lower frequencies. In order to combat these undesirable effects, the use of a copropagating pump at shorter wavelengths is known as an effective measure [8]. However, the copropagating pump has to be of lower noise than the counterpropagating pump, because the noise of the copropagating pump will transfer to the signal; the signal sees the temporally varying gain corresponding to the pump noise as they copropagate with each other, while in the counterpropagating case, the noise of the pump is "washed out" through counterpropagation [9]. Accordingly, a low-noise high power pump laser for copropagating Raman pump is important.

By all means, the key device of DRA is the pump laser. DRA had not become commercially attractive until appropriate high-power pump lasers came into market. Let us look into the pump laser technologies. For *C*- and *L*-band purposes, the Raman pump lasers have various wavelengths ranging from 1400 to 1500 nm. Therefore, such pump lasers are often referred to as 14XX-nm pumps [10]. It was a coincidence that the technology for 14XX-nm lasers was compatible with that of 1480-nm pump lasers for EDFAs, or *vice versa*. Once the demand for Raman amplifiers increased in the context of the rapid deployment of WDM systems, practical 14XX-nm pump lasers readily became commercially available at a reasonable price. One of the most important characteristics of 14XX-nm pump lasers is, of course, the high power output, preferably as high as possible. There have been extensive development activities on diode Raman pumping sources. Table 1 shows

Table 1 Typical Types of Pump Laser for Raman Pumping Unit

Types	Laser chip structure	Package structure
FP laser		
IGM laser		
FBG laser		
Hybrid pump		

typical types of pump lasers developed so far. All FP lasers, IGM lasers, and FBG lasers are powerful enough for WDM-pumped Raman applications. The nominal output power of these lasers well exceeds 300 mW.

Fig. 9 plots the transition of nominal pump power output available in the market. It is seen in Fig. 9 that the WDM bubble peak in 2001 triggered the rapid development of high-power Raman pumps. In fact, the latest 14XX-nm laser diode chip emits a power of more than 500 mW from its facet with the power density as high as 20 MW/cm^2, and the design limits of high-power laser diodes with the given material have nearly been reached. Notwithstanding such ultimate engineering, the reliable operation of these laser diodes has been field-proven. Also, in a screening test, 14XX-nm pump lasers exhibit very low failure rate. Fig. 10 shows the aging drift. An estimate based on these data shows 1 million h of median lifetime for 275-mW fiber-coupled power in a 1.5-mm cavity laser chip at 25 °C. A median life of tens of years is usually required in each of the components in telecommunication systems, and these pump lasers exhibit superior reliability to meet this demand.

In addition to the high-power feature, the pump lasers for Raman amplifiers require special design considerations. That is, the stability of both pump power and wavelength determines the stability of Raman gain. However, a stable low-noise single-frequency laser at high-power operation usually suffers from an adverse nonlinear effect called stimulated Brillouin scattering (SBS), which causes a significant reflection of input light in fiber with enormous amount of noise, and may completely destroy the signal quality. In fact, there is a fundamental tradeoff between intensity noise and laser linewidth. Therefore, in principle, high-power pump lasers tend to be of multilongitudinal mode entailing poor intensity noise performance in order to better avoid SBS.

In order to realize efficient WDM pumping, a narrow lasing spectral envelope is also important. A fiber Bragg grating (FBG) stabilized pump laser is the most suitable pump laser for Raman amplification, because, while lasing in multimode and achieving a very high SBS threshold, the oscillating wavelength envelope is narrowed and stabilized by the stable FBG reflector. However, FBG lasers entail poor intensity noise due to the fundamental tradeoff.

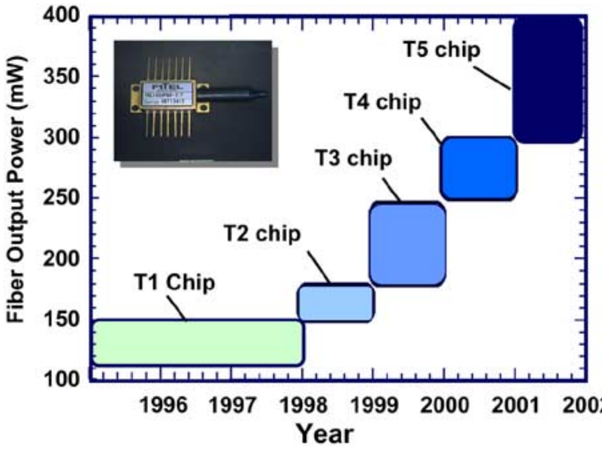


Fig. 9. *Transition of nominal pump power output available in the market. Inset shows the appearance of a pump laser.*

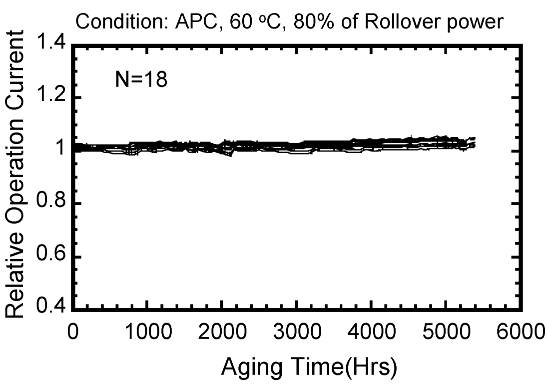


Fig. 10. *Aging drift curve of high power 14XX-nm pump laser diodes.*

Therefore, FBG lasers are mostly good for counterpropagating pumps. A conventional Fabry–Perot (FP) laser shows a low intensity noise. However, the operating wavelength is sensitive to both temperature and current, while the spectral envelope is too wide for WDM pumping. In order to solve such shortcomings of FBG and FP lasers at one time, a new type of pump laser called the IGM laser was developed for copropagating the pump [8]. The IGM laser integrates a wavelength stabilizer within the diode chip to narrow and stabilize the spectral envelope while the intensity noise is suppressed at the fundamental tradeoff limit. Fig. 11 plots the relative intensity noise spectra for various pump lasers.

Another type of pump laser, called the hybrid pump, has been developed for ever high output power. The hybrid pump laser chip carries double-stripe active regions and emits laser output at two spots. The two emitted beams are polarization-combined inside the package simultaneously and efficiently coupled with identical single-mode fiber.

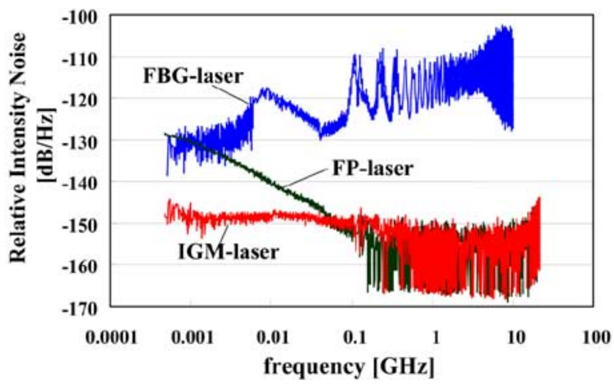


Fig. 11. *Relative intensity noise spectra of various types of pump lasers.*

Because of the double-stripe structure, the coupled output power from the fiber can be nearly twice of the conventional pump lasers, enabling more than 600-mW output.

V. ISSUES ON SAFETY AND OPTICAL DAMAGE

The challenges of the Raman technologies in early stages had been the ever high-power output of pump lasers. On the other hand, the challenges now are turning to the high-power limits of eye safety as well as optical damages of passive fiberoptic components. Because of the commercial availability of watt-class pumping units in Raman technologies, as reviewed above, considerations of eye safety and optical damages have become a serious issue as they are increasingly deployed in the real systems.

Studies on the eye safety of laser sources can be found in a document compiled by the International Electrotechnical Commission (IEC) [11]. Recently, a working group of IEC on optical amplifiers, IEC SC86C/WG3, has been compiling a comprehensive report on eye safety and optical damage related to high-power optical amplifiers on the ground that the total average optical power in optical transmission systems are rapidly increasing year by year, particularly due to massive WDM systems and advent of Raman amplifiers [12]. According to this report, eye safety can be maintained by proper handling of optical fibers and management of laser sources. While it is suggested to introduce training of technicians for such proper handling, at the same time, an automated safety system such as automatic power reduction (APR) or automatic laser shutdown (ALS) should be developed for the prevention of hazards due to high power optical leakage from optical fiber cables. For example, in an "unrestricted location," or under the condition of a 10-cm nominal ocular hazard distance (NOHD), if the power reduction time of APR is 1 s, the maximum permissible exposure (MPE) at 1480 nm is equivalent to 936-mW output power from a fiber facet

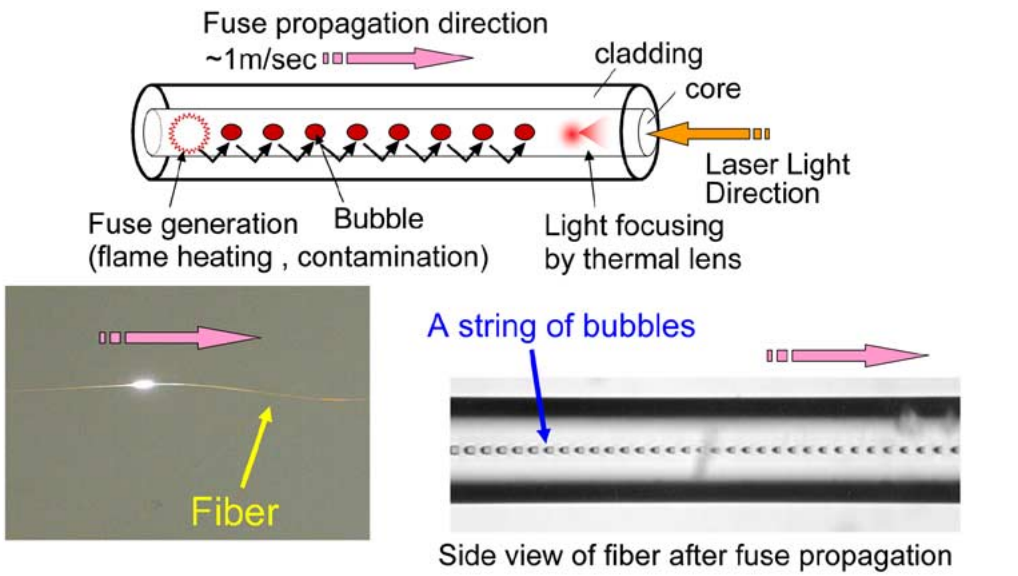


Fig. 12. ***Fiber fuse phenomenon. Visible light characterizes the propagation of fiber fuse.***

with a mode field diameter of 9.1 μm. In a "controlled location," where NOHD is 25 cm for trained technicians and the power reduction time is 3 s, MPE at 1480 nm becomes 2.59 W for the same fiber. A detailed guideline for APR procedures can be found in an ITU-T recommendation [13]. APR is also important because of the possible optical damages caused by high-power exposure, leading to the risk of fire when the fiber is broken or very tightly bent.

Optical damages of Raman amplifiers may occur due to various causes at various places along the fiber waveguide. In the core of fibers, a catastrophic optical damage called fiber-fuse is reported to occur when high optical power propagates in silica glass fiber. A high optical power leakage due to accidental extremely tight bending of fiber cable could fire the cable. And fiber facets such as connector end faces can be optically damaged especially due to dirt or contaminations. According to the IEC technical report [12], these plausible optical damages are avoidable by knowing their thresholds.

A. Fiber Fuse

Fiber fuse may be observed when very high optical power is launched into one end of a fiber. A whole picture of fiber fuse is illustrated in Fig. 12. The fuse could be initiated by contacting, heating, or contaminating the other end of the fiber. This phenomenon entails the propagation of a bright visible light from the point of initiation toward the laser source. A side view of the fiber after fuse propagation is also shown in Fig. 12. The core region of the fiber exhibits a periodical void structure, completely devastating the waveguide feature. This phenomenon should be avoided, as a long length of transmission fiber could be damaged.

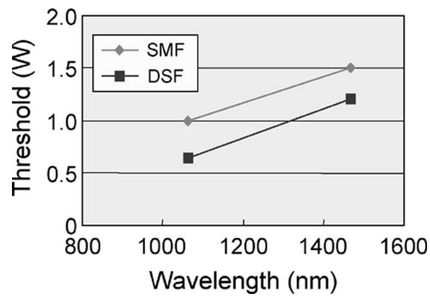


Fig. 13. ***Propagation threshold power versus wavelength for SMF and DSF.***

There are two threshold values of optical power density to characterize the fiber fuse: one for initiation and the other for propagation. The initiation of fiber fuse is in fact difficult to reproduce even in lab experiments. One of the authors demonstrated that a launch power of 5 W at both 1064 and 1467 nm could steadily reproduce the fuse initiation with the aid of heating with arc discharge [14]. The threshold for propagation can be measured once the fuse is initiated, namely, the decreased launch power at which the propagation stops.

Although the fuse does not start spontaneously even at a launch power of 5 W for both SMF and DSF, it could easily occur under the above-mentioned special circumstances. In order to surely avoid the fuse, the operating power should be below the propagation threshold. In this

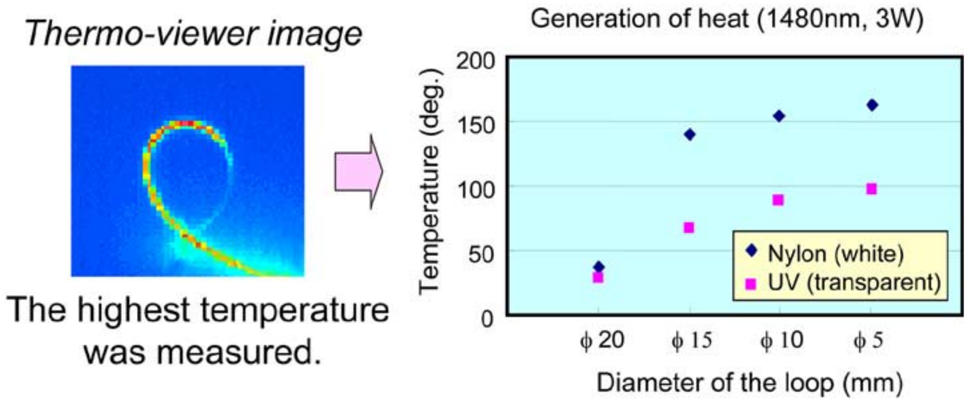


Fig. 14. *Thermoviewer image (left) and temperature at the surface of the coating depending on the diameter of the bending (right).*

sense, it is important to carefully assess it for the fibers being used. Fig. 13 shows the propagation threshold power versus wavelength for SMF and DSF. For telecom purposes, Fig. 13 suggests that at least up to 1 W could be free of fiber fuse.

As the fuse initiation is not always automatic even up to launch powers of several watts, further studies can reveal that much higher launch power could be allowed under certain conditions.

B. Burning Due to Tight Bending

A standard telecom SMF is not so designed to be bent in a small radius such as 10 mm. However, in actual use, a fiber cable could be accidentally bent in a much smaller radius without breaking for a certain period. In such a case, a part of the light propagating the fiber leaks out of the core to the outer coating of the fiber cable. If the leaked power is very high, then the coating material absorbs it, resulting in a temperature increase. The increase of temperature may burn the cable to cause fire. Fig. 14 shows the temperature at the surface of the coating depending on the diameter of the bending, in which the inset shows an image by thermoviewer.

In this figure, two kinds of coating material were tested: one was white nylon coating and the other was transparent UV coating. From the plot, the transparent UV coating shows better endurance against the high-power leakage. Although this data is just a unique example, it is enough for suggesting the use of particular coating material for better reliability.

C. Connector Damage

Many optical fiber connectors are used in real systems, although it is desirable not to use connectors in order to avoid unwanted optical signal reflections as well as connector end face damages due to the use of very high power. It is well known that the contamination of phosphor bronze at the end face of the connector causes optical

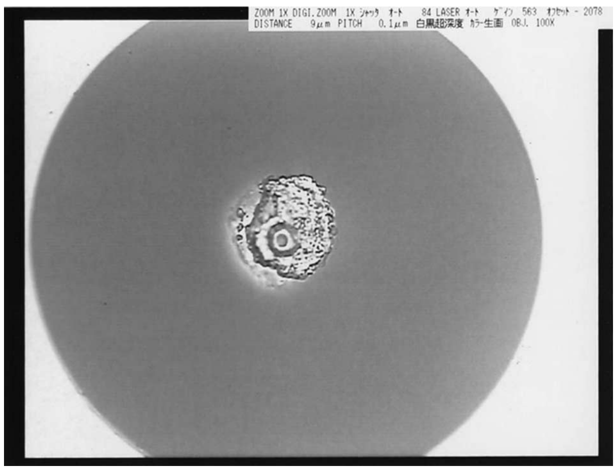


Fig. 15. *Photograph of optically damaged end face of a connector.*

damages very easily at an optical power of only 30–50 mW. Fig. 15 shows the optically damaged end face of a connector. The excess loss due to the damage is typically 50%–70%.

In our previous paper [14], various contaminations were tested. As a result, ethanol and oil from human hands did not do anything, while the contaminations of epoxy resin with carbon, nickel plating, and oil-based black ink showed temperature increase at the connector under high-power exposure. Particularly, black ink and phosphor bronze were almost 100% responsible for causing optical damage, even causing fiber fuse. Again, our experiments revealed that the use of index matching oil causes temperature rising, which suggests avoiding its use for high-power operations. Scratching on the connector end faces showed no effect as long as the connector loss is not noticeably increased. However, the above contaminations caused optical damage even though the excess loss was negligible. In any case, cleaning of connectors should be strictly performed in order to avoid the temperature rising or the risk of optical damage.

VI. OUTLOOK FOR FUTURE

Although the telecom industry is suffering from severe cost reduction pressure for cutting-edge technologies, Raman amplification provides unique compelling advantages in terms of both bandwidth and transmission performance. And the key pump technologies are now mature enough for widespread use. Beyond cost issues, the reliability of handling high power may be the last challenge of Raman technologies. So far, we have seen that there are effective countermeasures. However, as the studies on eye safety and optical damage have just begun, it is important to further continue the detailed and extensive studies to find better and decisive countermeasures. It is also true that the human handling is the ultimate issue, while the continuing studies should clarify the proper and easy guidelines for the widespread use of Raman amplifiers. In this regard, international standardization organizations such as the IEC and the ITU should play an important role. Again, because of the compelling advantages of Raman amplifiers, it is highly expected that the technologies will overcome the issues on eye safety and optical damage, and that there will be many of well-trained technicians for the safe deployment and maintenance. In fact, a successful field trial result of a Raman amplified system has been reported taking into account such safety issues and related practical implementations [15].

Finally, it should be noted that many other means in the electronic domain have also been extensively developed to improve transmission performance, such as forward error corrections, which are certainly of good use for improving system performance. However, optical and electronic means are complementary with each other. And as long as the systems continue to improve and increase the capacity, optical approaches will eventually become more efficient and hence indispensable in the long run. Considering the rapid growth of traffic, it may not be too far in the future that Raman amplifiers will be used in many transmission systems in service. ■

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