Ultra-large-area Low-loss Fibers and Advanced Amplifiers for Large Capacity Long Haul Optical Networks

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ABSTRACT This paper reviews recent progress on ultra-large-area low-loss fibers for next generation large capacity terrestrial long haul optical networks. The key optical fiber properties and their impacts on the transmission performance for 400 Gb/s polarization division multiplexing (PDM) coherent transmissions are discussed; and the practical consideration of the large-area fibers, such as splicing and cabling for terrestrial transport systems is also briefly addressed. In addition, we describe two advanced optical fiber amplifier technologies that will improve the efficiency in utilization of optical networking resources and reduce total system costs. The design and performance of arrayed optical fiber amplifier using a compact ribbonized erbium doped fiber (EDF) for next generation reconfigurable optical add/drop multiplexer (ROADM) nodes are discussed, and the performance characteristics of complementary Raman/erbium doped fiber amplifier (EDFA) for seamless C+L band transmissions are described.

1. INTRODUCTION

In recent years, optical transmission technology has advanced rapidly with the combination of multi-level modulation formats, coherent detection and digital signal processing (DSP). 100 Gb/s optical transport systems have been widely deployed, and 400 Gb/s and 1 Tb/s super-channels have been demonstrated in laboratories and field trials. While transmission technology is to transmit large capacity at higher data rate over longer distances, optical networking is now gradually evolving towards elastic optical network (EON) or flex-grid optical network architecture[1), 2)] in order to make better use of optical network resources to accommodate the ever-increasing traffic demand. A combination of transmission and networking technologies can help to make effective use of available optical networking resources. However, the most fundamental improvement to the efficiency in utilization of optical network resources is to optimize the optical fiber cabling infrastructures that provide better capacity upgrade pathways and ensure sufficient transmission margins. Transmission fibers have historically, been critical to the enormous success of optical communication technology. Optical fibers as one of the enabling technologies used for optical networks have evolved for several decades and their optical properties have been engineered for low system cost and high transmission performance. Recently, major optical fiber cable companies are focused on research and development (R&D) on a new class of transmission fibers[3)-7)] that have large effective areas (A_{eff}) and ultra-low attenuation for 400 G and beyond PDM coherent transport systems. Another effective way is to improve amplification technologies that are widely utilized in optical network.

In this paper, we will describe the recent development of new ultra-large-area low-loss fibers and advanced amplifier technologies for next generation high capacity terrestrial long haul optical networks. Section 2 describes the key optical fiber properties of new class fibers and discusses their impacts on the transmission performance for 400 Gb/s multi-level modulated coherent transport systems; practical consideration of the large-area fibers, such as splicing and cabling for terrestrial optical networks will briefly be addressed; and the experimental results of transmission performance of new large-area low-loss fibers on a number of advanced high order modulation format systems will also be reviewed. We then describe two advanced optical fiber amplifiers that will improve the efficiency in utilization of optical network resources and reduce total system cost. Section 3 will discuss the design and performance of an arrayed optical fiber amplifier using a compact EDF ribbon for next generation ROADM nodes. Section 4 will describe the ultra-wide band complementary Raman/EDFA that has +70 nm bandwidth for seamless C+L band transmissions; the experimental demonstration of transmission 34.6 Tb/s

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capacity in single band over 2400 km fiber will be presented. A brief conclusion will finally be drawn in Section 5.

2. ULTRA-LARGE-AREA LOW LOSS FIBERS

Next generation optical networks will deploy 400 Gb/s and beyond transport systems which employ coherent digital detection and PDM high level modulation formats such as 16QAM. In such systems, the chromatic dispersion and polarization mode dispersion (PMD) can be digitally compensated in the electrical domain. However, with wavelength division multiplexing (WDM), the cross-nonlinearities make neighboring channels interact depending not only on their power but also on the state of polarization (SOP) of signals in such system. The last is particularly problematic in polarization multiplexed coherent systems, as this is more sensitive to cross-polarization modulation (XPolM)[8], which is associated with nonlinear polarization rotation in fiber transmission links. This XPolM does not have effect on non-return to zero (NRZ) non-coherent transmission system, but it impacts on coherent system because the polarization tracking in digital receivers cannot follow fast (symbol-to-symbol) polarization changes. As a result, the polarization-multiplexed coherent systems, particularly for high order quadrature amplitude modulation (QAM), are more susceptible to fiber nonlinear effects. Early research work showed at least 2-3 dB more nonlinear power penalties in quadrature phase shift keying (QPSK) coherent system compared to that in direct detection systems[9]. This XPolM nonlinear effect is stochastic in nature from fiber transmission links; hence it impairs the effectiveness of digital compensation. In addition, the high level modulation formats require much higher optical signal to noise ratio (OSNR). For example, in order to achieve the same performance at the same transmission distance, upgrade from QPSK based 100 Gb/s to 16QAM based 200 Gb/s, and 400 Gb/s require an OSNR improvement of about 6.5 dB and 10 dB respectively. Hence it is desirable to use new fiber types that have low nonlinear coefficients to retain the long haul transmission capability when scaling up the spectral efficiency (SE) and the per-channel data rate. Recently, a new class of transmission fibers with ultra-large A_{eff} in a range of 120-155 μm^2 and the attenuation as low as 0.1460 dB/km has been reported for both terrestrial and submarine systems[3)-7)].

To reduce the fiber nonlinearity, which is proportional to n_2/A_{eff}, where n_2 is the nonlinear refractive index, it is necessary to increase A_{eff} of fiber while not jeopardizing the bending performances. Step index profiles with small index differences and large core diameters can be used to design large A_{eff} fibers. However, the light confinement in the core becomes weaker, increasing the cut-off wavelength and degrading both macro- and micro-bending performance. Placing a depressed index region in the cladding, or placing a trench, slightly apart from the core can improve the bending performance and reduce the cut-off wavelength[4)]. A low Young's modulus primary coating[6)] can also be used to improve the micro- and macro-bending performance and to permit a larger fiber A_{eff}. It is also important to have high chromatic dispersion in new fibers to reduce nonlinear effects in the PDM coherent systems where chromatic dispersion can be digitally compensated.

In order to evaluate the system performance of different type fibers, a fiber figure of merit (FOM) has been developed based on the Gaussian noise model[10)]. This FOM is based on the maximization of reach, given a target bit error rate (BER) for the transmission of dense wavelength division multiplexing (DWDM) multi-level modulation format signals over uncompensated links. Here we use a simplified version of that fiber FOM as given in Eq. (1), in which the FOM is defined in a relative reach of new fiber to a reference fiber. It is assumed that the dispersion is essentially equivalent for high dispersion fibers such as those described by the ITU-T G.654 standard[11)], and that the systems use EDFA-only with the same noise figure (NF) for all fibers. An optimal launch signal power into each span is assumed for all fibers and miscellaneous loss components are ignored.

$$FOM(dB)=\frac{2}{3}\left\{10\log\left[\frac{A_{eff}/n_2}{A_{eff,ref}/n_{2,ref}}\right]-\left[\alpha_{dB}-\alpha_{dB,ref}\right]\bullet L-10\log\left[\frac{L_{eff}}{L_{eff,ref}}\right]\right\} \quad (1)$$

where A_{eff} is the fiber effective area, n_2 is the nonlinear refractive index, α_{dB} is the fiber attenuation in units of dB/km, L is the spans length of the repeatered system being considered, and L_{eff} is the nonlinear effective length. The terms with "ref" in the subscript refer to the reference fiber. The effective length L_{eff} is defined as the following where α is in linear units

$$L_{eff}=\frac{(1-\exp[-\alpha L])}{\alpha} \quad (2)$$

The first term in Eq. (1) takes into account the improvement from A_{eff} and nonlinear refractive index n_2, the second term is from the fiber attenuation (α in dB/km), and third term from fiber L_{eff}. It can be seen from (1) that increasing the fiber A_{eff} is the most fundamental improvement for coherent transport, and reducing fiber attenuation can improve span loss. However, the reduction of fiber attenuation will increase fiber effective nonlinear length, hence increase the accumulated nonlinear impairments (the third term in (1)). An example of contour maps of relative FOM results are shown in Figure 1 where the reference fiber is chosen to have attenuation of 0.20 dB/km, and A_{eff} of 80 μm^2, comparable to many standard single mode fiber (SSMF), and the span length is 80 km. The results plotted in Figure 1 show clearly that increasing effective area and reducing the fiber attenuation lead to increased FOM and better system performance. It should be noted that there is a discontinuity between the attenuation values of 0.174 and 0.175 dB/km in Figure 1, this reflects the assumption made here that the attenuation values below 0.175 dB/km are achieved with pure silica core fibers with a lower nonlinear index n_2 compared to Ge doped silica fibers[12]. It should also be pointed out that the relative reach improvement in FOM depends on the span length of the transmission systems.

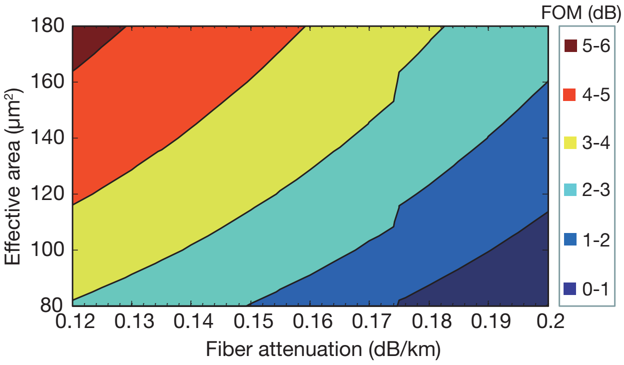

Figure 1 Relative fiber FOM as a function of attenuation and effective area for 80 km spans in long haul systems.

We have recently developed large A_{eff} TeraWave fiber for 100 G and beyond terrestrial long haul optical networks. The TeraWave fiber is a single mode fiber with a germanium doped core and a depressed index inner cladding region, and is fabricated similarly as AllWave zero water peak (ZWP) fiber. Considering the features of terrestrial cabling such as craft splicing, closures, macro- and micro-bending, the A_{eff} of TeraWave fiber is optimized to be 125 μm^2. The average fiber loss, dispersion, and dispersion slope at 1550 nm are 0.184 dB/km, 20.0 ps/nm/km, and 0.06 ps/nm^2/km, respectively. TeraWave fiber is ITUT G.654.B[11] compliant, and it uses the DLUX Ultra coating for excellent micro-bending performance, and it meets all macro-bending requirements in G.652.D and G.654.B. Volume splicing study using commercially available splicer (for example Fitel S178A) with standard splice recipe shows that the averaged splice loss between TeraWave to TeraWave is 0.04 dB/splice, and TeraWave to SSMF is about 0.15 dB/splice. With optimization of splicing programs using commercially available splicers, the splicing loss between TeraWave to SSMF is below 0.10 dB/splice.

We have also recently developed TeraWave ultra-low-loss single mode optical fiber which is a 125 μm^2 large area ultra-low-loss fiber, and the averaged fiber loss and dispersion at 1550 nm are 0.168 dB/km and 20.0 ps/nm/km respectively. The fiber is optimized for long haul transmission in the C and L bands (1530 nm-1625 nm) at 100 Gb/s, 400 Gb/s and beyond for terrestrial optical networks, and it supports greater distances between regeneration and amplification sites, helping to lower the overall cost of deploying coherent systems.

We have systematic experimentally investigated the system performance of TeraWave fiber in a 485 Gb/s coherent optical orthogonal frequency-division multiplexed (CO-OFDM) super-channel long haul transmission system[3], and compared with the SSMF. The CO-OFDM super-channel coherent system has the advantages including high SE, reduced guard band, and lower modulation baud rate, and it is a potential candidate for future high capacity Tb/s per channel optical networks. However, the CO-OFDM super-channel systems are more susceptible to fiber nonlinearity when compared with other schemes. This is because the multi-subcarrier configuration with small guard band in CO-OFDM transmission leads to the impairment of inter-subcarrier nonlinear interference. In the experiment, the 485 Gb/s CO-OFDM was generated with PDM-16QAM five-subcarrier modulation, and it was done with dispersion uncompensated link with 80 km fiber span length using two amplification schemes, EDFAs and hybrid EDFA/Raman amplifiers. The comparison experiment showed that the optimum signal launch power into fiber spans is about 2 dB higher in TeraWave fiber than in SSMF for transmitting of 485 Gb/s CO-OFDM signals over 1600 km (20x80 km) spans under both EDFA-only and hybrid Raman/EDFA amplification schemes. With EDFA-only amplification, the TeraWave fiber offers ~2 dB higher optimum Q^2 factor than the SSMF after 1600 km transmission. It is about 1 dB higher for the hybrid amplification scheme (Figure 2). It also was found that TeraWave fiber allows transmission more than 60% longer than SSMF link at the similar Q^2 factor performance for 400 G OC-OFDM systems.

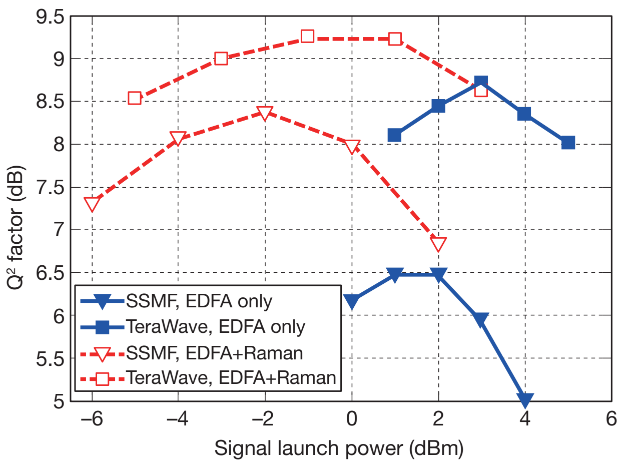

Figure 2 Measured Q^2 vs launch powers of 485 Gb/s CO-OFDM signal transmission over 1600 km of TeraWave and SSMF[3].

We have further experimentally investigated the transmission performance of TeraWave fiber in a typical 256 Gb/s PDM-16QAM DWDM system with 37.5 GHz and 50 GHz channel spacing[13]. The 256 Gb/s PDM-16QAM is a promising modulation format for two carrier 400 Gb/s systems due to relative simple scheme and maturity of opt-electronic components. The experiment was conducted with dispersion uncompensated link with 100 km fiber span length using three different amplification schemes, including EDFA-only, hybrid EDFA/Raman amplifiers and all backward-pumped Raman amplifiers. It has been found that that when there is no ROADM, ten 256 Gb/s PDM-16QAM channels were transmitted over 4200 km, 3500 km, and 2000 km over TeraWave fibers within a 20% soft-decision forward error correction (SD-FEC) threshold respectively in the system with both 37.5 GHz and 50 GHz channel spacing (see Figure 3). The all backward-pumped Raman amplifiers and hybrid EDFA/Raman amplifiers can increase the transmission distances by about 100% and 70% respectively when compared with EDFA-only amplifiers. It was also found that cascaded ROADMs have a small impact on the system with the 50 GHz channel spacing.

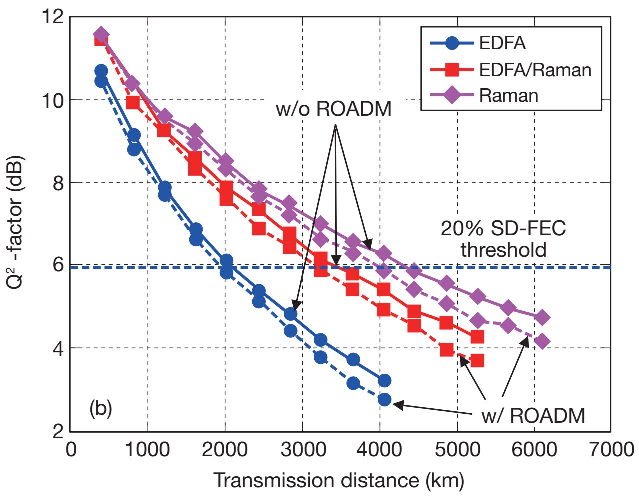

Figure 3 **Q^2 factor versus transmission distance of the 10-channel 256 Gb/s PDM-16QAM system using the three different amplification schemes without (solid curves) and with ROADMs (dashed curves) with 50 GHz channel spacing. Optimum launch powers are used.**

The large-area low-loss fiber has also been studied in other advanced higher order modulation format systems, for example, time domain hybrid 32-64 QAM, for high SE 400 Gb/s ultra-long haul transmission systems[14], and it has been demonstrated that the 400 Gb/s class DWDM signals on the standard 50 GHz ITU-T grid, which is 8.25 b/s/Hz net SE, were transmitted over 4000 km of large-area low-loss fiber with 100 km span length for terrestrial optical network.

The above results demonstrated that the large-area low-loss fibers are indeed beneficial for system reach and margin irrespective of amplifier configuration, and they increase system SE, and have much better efficiency in utilization of optical network resources for future EON. Further enlargement of A_{eff} (e.g. >200 μm^2) would inevitably deteriorate bending and cut-off behavior and cause high splicing loss. Hence fiber design compromises must be made between improved transmission performance and limitations from careful handling and splicing of new fibers.

3. ARRAYED AMPLIFIERS USING RIBBONIZED EDF

The future optical network will not only be able to trade-off between SE and system reach, but also provide more networking flexibility in terms of wavelength path routing, switching and assignments. In such networks, multiple degree ROADM with colorless, directionless, contention-less (CDC) functions is expected to play an important role for realizing dynamic capacity allocation[15]. However, the insertion loss of the ROADM nodes with these sophisticated functions is generally higher than that for the basic 2 degree node. As a result, an optical amplifier array with 1x8 or 1x16 is often required in order to compensate additional insertion losses in Mx1 wavelength selective switches (WSS) and 1xN optical coupler[15]. Currently, a number of discrete EDFA modules using separately pump diodes are usually employed. As the degree of ROADM increases, the ROADM become bulky, costly and inefficient due to many such individual EDFA. For example, if we assume that a commercially available module is installed between a 1x4 WSS and 4x1 optical coupler in the CDC ROADM node, a few hundred discrete EDFA modules are required in a single node[15]. This approach would become undesirable in terms of equipment size and cost when the degree of ROADM is increased. As a result, a compact arrayed EDFA can be beneficial in reducing the array module size and manufacturing cost for future ROADM nodes.

The concept of arrayed optical amplifier by shared pump lights have been proposed to reduce amplifier array module size, however these approaches use either discrete EDF[16], which occupy a large space, or use erbium doped waveguide amplifier (EDWA)[17], which is still not widely commercialized due to its poor performance. We recently have proposed and designed an arrayed fiber amplifier using ribbonized EDF to reduce the EDFA array module size and manufacturing cost (e.g. with one ribbon EDF coil instead of making 8 EDF coils). A schematic of compact arrayed EDFA using EDF ribbon is shown in Figure 4, and it is composed of optical isolators, WDM combiners, and EDF ribbon, and configured in a co-propagation pumping scheme. Other functions such as gain flattening and input/output signal monitors can also be implemented.

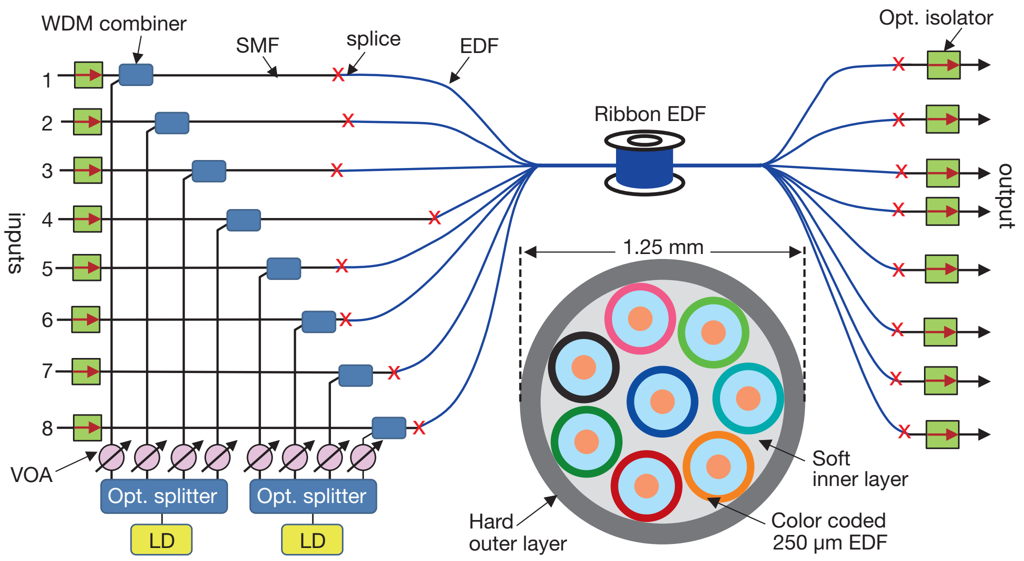

Figure 4 **Schematic diagram of 1x8 arrayed EDFA, inset: schematic of 8 EDF ribbon; (b) Measured gain and gain deviation of individual EDFA in arrayed EDFA.**

A schematic diagram of 8 EDF ribbon is shown in inset of Figure 4. The EDF ribbon includes a plurality of individually coated EDF arranged in a close-packed round shape; a colored ink layer is applied over each individual EDF coating for easy identification. The colored EDF are encased in a two layer structure, in which a soft UV cured inner layer is used to cushion fibers, and a hard UV cured outer layer is used to protect fibers. In order to obtain the same amplification performance of each EDFA in the array, the each individual EDF within ribbon have the same optical properties such as erbium absorption, MFD, cut-off wavelength and background loss. Table 1 shows the peak absorption of each EDF in the ribbon with the average peak absorption of 6.49 dB/m and standard deviation of 0.04 dB/m, showing good uniformity of the EDF. The EDF ribbon is peelable for easy fiber access, and it is made in a round shape for easy package. The EDF ribbon has the diameter of 1.25 mm and can be coined in a compact form. The ribbon diameter can be further reduced by using 125/200 µm or 80/165 µm cladding/coating diameter EDF respectively. The input/output of individual EDF can be separated by peeling off from the ribbon EDF and spliced to other fiber components. Pump power can be shared by multiple EDFs, for example, by splitting power from one diode into multiple portions, with each portion used to pump individual EDFs in the ribbon. Power can be managed using individual variable optical attenuators (VOA). So the arrayed EDFA can be made in very compact, efficiency and low cost.

Table 1 **Peak absorption of individual EDF in ribbon EDF.**

	EDF1	EDF2	EDF3	EDF4	EDF5	EDF6	EDF7	EDF8
Peak Absp (dB/m)	6.43	6.51	6.41	6.52	6.52	6.48	6.48	6.51

We developed a solid 8 EDF ribbon in a round shape with a diameter of 1.25 mm, and experimentally investigated the performance of the arrayed EDFA by using a 1x8 ribbonized EDF. Each EDFA in the 1x8 arrayed amplifier was pumped by 976 nm LD 405 mW pump power in a co-propagation pumping scheme, and a 12 meter length of ribbon EDF was employed in the experiment. Figure 5 shows the measured gain and the gain deviation from the averaged gain curve for each EDFA in the 1x8 arrayed EDFA. The average gain of 19.3 dB is obtained with average output power of 21.9 dBm; and the gain deviations were <±0.8%, exhibiting excellent gain shape uniformity among the EDFA within the array. This gain deviation can be further reduced by slightly adjusting the length of individual EDF and the pump power. The measured NF of 8 EDFA from the arrayed EDFA are ranging from 3.5 dB to 4.8 dB across C band for 8 EDFA, showing good performance of the arrayed EDFA.

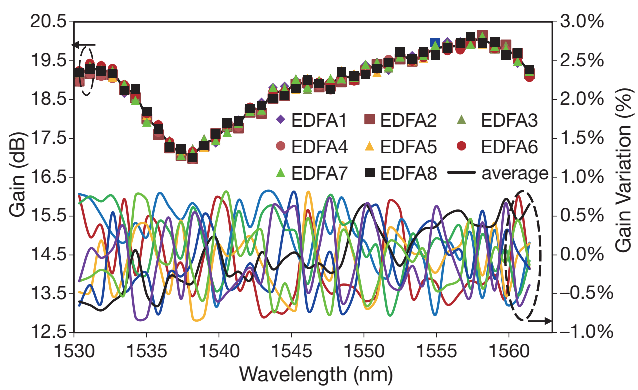

Figure 5 **Measured gain and gain deviation of individual EDFA in arrayed EDFA.**

4. ULTRA-WIDE COMPLEMENTARY RAMAN/EDFA FOR SEAMLESS C+L BAND TRANSMISSION

One of important features for next generation optical network is to improve the efficiency in utilization of optical network resource. It is well known that optical fiber has tremendous transmission bandwidth (e.g., +9 THz bandwidth in C+L band). However, currently major network operators deploy optical fiber transport systems only in either C band or L band with the bandwidth around 4 THz using EDFA. Multi-band transmission systems have been considered to increase capacity in a single fiber. Typical C+L band systems with separate C and L band EDFAs require guard bands of 8 nm or more near 1565 nm. A seamless C+L transmission band avoids the band splitters and combiners required by systems with C+L EDFAs, thus simplifying the system configuration and potentially lowering overall system cost. In addition, the reduced number of loss elements due to the C+L band splitter/combiners along the transmission link may result in higher received OSNR, thus improving system performance. One of the technical challenges for such ultra-wide band transport system is the high efficiency seamless wide band optical amplifier. In this section, we describe the design and performance characteristics of ultra-wide band complementary Raman/EDFAs that have the flat bandwidth of +70 nm and present the experimental results of 34.6 Gb/s single band transmission over 2400 km of TeraWave fiber using this complementary Raman/EDFA.

A. Complementary Raman/EDFA

The simple scheme of the complementary Raman/EDFA is shown in Figure 6. Each of EDFA and Raman amplifiers covers a different portion of gains for C and L band, and they are combined in a serial cascade. In this example, the EDFA section is a standard single stage 980 nm forward-pumped scheme using commercially available EDF. The EDFA section mainly provides the gain for C band, whereas backward-pumped distributed Raman amplification from transmission line using the pump lasers at pump wavelength around 1490 nm provides the L band gain. Here a 100 km TeraWave fiber span was used for the transmission line. The TeraWave fiber used in this experiment has 0.182 dB/km attenuation at 1550 nm, and its peak Raman gain efficiency at 1550 nm is 0.25/(W.km). A gain flattening filter (GFF) is designed and inserted between Raman and EDFA to equalize the combined Raman EDFA gain shape, a fixed GFF was used in this experiment. Compared the use of C+L two separate EDFA case, where C/L wavelength band coupler/splitter are used, in this simple structure, only a few optical components are needed, so it is cost effective. The gain bandwidth of the complementary Raman/EDFA can be as large as about 80 nm (1530 to 1610 nm). A wide band flat gain of this amplifier can be obtained; however, the NF may not be flat over the bandwidth.

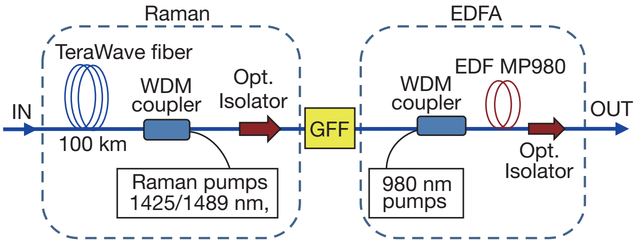

Figure 6 Schematic diagram of complementary Raman/EDFA for 100 km TeraWave fiber span;

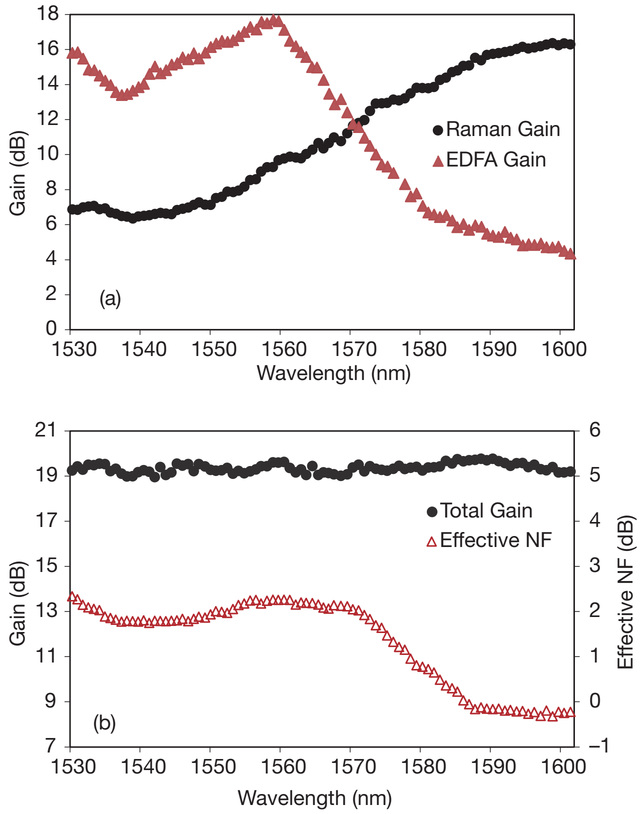

Figure 7 (a) Measured EDFA gain and Raman gain from the complementary Raman/EDFA, (b) measured total gain w/ GFF and effective NF.

In order to improve the flatness of NF, which will be important for a relative flat OSNR over the wide C+L band, additional Raman pump lasers at multiple different wavelengths can be employed. We fabricated a 73 nm bandwidth complementary Raman/EDFA using two pump wavelengths (1425/1489 nm). In this design, the EDFA section used 9.5 m of OFS MP980 EDF pumped by a 980 nm diode with 460 mW pump power. Commercially available semiconductor diodes were used as the Raman pumps after being de-polarization using polarization beam combiner. The measured EDFA and Raman on-off gain are plotted in Figure 7 (a) when the pump powers at 1425 nm and 1489 nm were 390 mW and 580 mW, respectively. It can be seen that about 7 dB Raman gain at short wavelength range in C band was obtained by the 1425 nm pump. The measured total gains after GFF and effective NF are shown in Figure 7 (b). The output power of the Raman/EDFA is 22.4 dBm and gain flatness is 0.82 dB. Gain values can be adjusted slightly by setting the pump powers in order to accommodate different span losses in real terrestrial systems. However the gain flatness will be affected if a fixed GFF used and an adaptive GFF can be implemented to further improve the gain flatness. It also can be seen that the effective NF of L band is lower than that in C band, which is due to the relative high gain from distributed Raman amplifications. It is a result of the distributed nature of the gain along the transmission fiber, compared to the lumped gain of the EDFA at the end of the fiber. The large A_{eff} TeraWave fiber provides a good balance between avoiding nonlinear impairments while allowing sufficiently high Raman efficiency so that high distributed gain can be achieved with < 1 W pump power using diodes at only two wavelengths.

B. 34.6 Tb/s Single-band and Transmissions

Several system demonstrations of ultra-wide, seamless band transmission were reported more than 10 years ago [18)-20)]. Recently, a 54 Tb/s transmission with a seamless bandwidth of ~73 nm has been demonstrated for submarine systems[21)], and ultra-wide seamless band transmissions of 9 Tb/s[22)] and 17.3 Tb/s[23)] have been reported for terrestrial network applications. Both all Raman distributed amplifiers and hybrid Raman/EDFA have been reported for the ultra-wide seamless band long haul transmission, compared to all Raman schemes, the complementary Raman/EDFA offers low pump consumption and possibly low overall cost for long haul network. Here, we describe an experimental demonstration of transmission of 34.6 Tb/s capacity in a 70 nm seamless band over 2400 km of TeraWave fiber.

The 34.6 Tb/s single-band transmission experiment was done by using 173x256 Gb/s PDM-16QAM DWDM channels with a dispersion uncompensated fiber link, and the experiment details was described in [24)]. The transmitters consisted of 173 distributed feedback (DFB) lasers and tunable external cavity laser (ECL) at wavelengths ranging from 1530.31 nm to 1600.60 nm on 50 GHz spaced ITU frequency grid. Commercially available four channel 64 GS/s digital-to-analog converters (DAC) were employed to generate 32 G baud 16QAM signals and offline DSP coherent receiver by 80 GS/s digital oscilloscope as the analog-to-digital converter (ADC) was used to evaluate system performance (BER counting, and Q^2 factor calculation)[24)]. Four units of complementary Raman/EDFA aforementioned were employed to compensate the loss of 100 km fiber spans in the recirculating loop experiment. The optimization of the transmission performance was carried out by pre-emphasis the output power of ECL for selected channels from the C and L band, and the total launched power into fiber spans were about 20.1 dBm which was limited by the output power from DRAs. Figure 8 (a) plots the performance of selected 4 channels vs the transmitter pre-emphasis power after 6 loops (2400 km) transmissions, and it indicates that the signal launched power in L band are slightly lower than these in C band. This is due to the fact the signal path average power (PAP) in L band are generally higher than these in C band, because the large portion of gain in the L band are contributed from distributed Raman gains. The Q factor of the selected 4 channels as a function of transmission distance is shown in Figure 8 (b), showing the L band channels can potentially have a reach of ~3200 km. The recovered signal constellation for x- and y-polarization of channel 1554.94 nm after 2400 km transmission is shown in inset of Figure 8 (b). Finally the channel powers in C+L seamless band were slightly pre-emphasized; the received optical spectrum after transmission is plotted in Figure 9 (a), showing the negative tilt of signal power about 3 dB across entire C+L band. The received OSNRs for 173 channels after 2400 km transmission ranged from 18.9 to 22.8 dB (in 0.1 nm RBW), with average of 20.7 dB (Figure 9 (b)). The average Q factor was 6.83 dB after 2400 km transmission, with the worst channel Q factor of 6.08 dB, which is above the SD-FEC threshold of 5.92 dB Q factor (BER 2.4x10^{-2}), and would yield a BER below 10^{-15} after correction by the SD-FEC[25)].

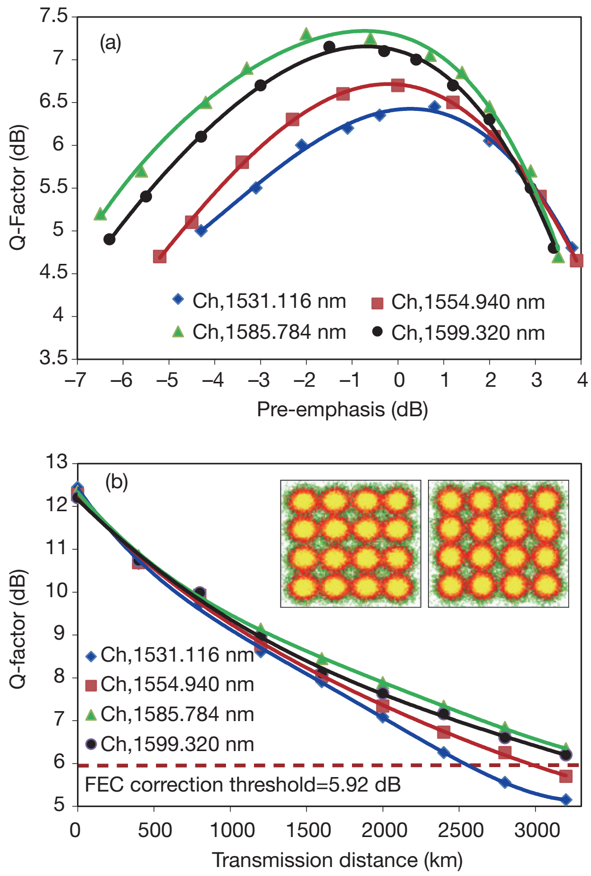

Figure 8 **Performance vs transmission distance, inset are the recovered constellations for x- and y-polarization of the channel 1554.94 after 2400 km.**

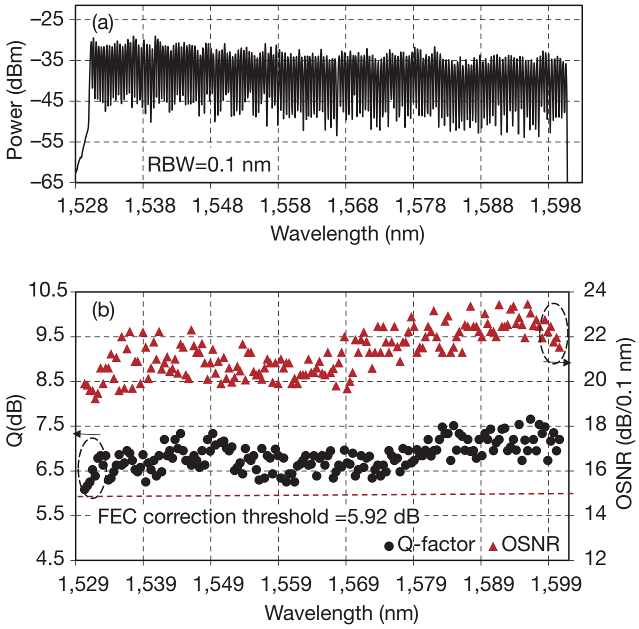

Figure 9 (a) Received optical spectrum, (b) received OSNR and measured Q-factors after 24x100 km transmission.

This demonstration indicates the potential high capacity seamless C+L band transmission by using the wideband complementary Raman/EDFA plus large-area low loss TeraWave fiber for long haul terrestrial optical network. The seamless band transmission permits the traffic upgrade smoothly and to be more flexible in routing and assignment of wavelength channel across C and L band for EON. As this experiment was done at 50 GHz channel spacing, the total capacity can be easily scaled up to +50 Tb/s for a single-band transport system by using 37.5 GHz channel spacing.

5. CONCLUSION

This paper reviewed new development of ultra-large-area low-loss fibers for next generation high capacity terrestrial long haul optical networks. The key optical fiber properties of new class fibers have been described and their impacts on the transmission performance for 400 Gb/s PDM multiple level modulation coherent transmissions have been discussed. In addition, we have described two advanced optical fiber amplifier technologies that improve the efficiency in utilization of optical networking and reduce total system costs. The design and performance of arrayed optical fiber amplifier using a compact ribbonized EDF for next generation ROADM nodes have been discussed; the design and characteristic of complementary Raman/EDFA that has +70 nm bandwidth for seamless C+L band transmissions also have been described. Finally the experimental demonstration of transmission 34.6 Tb/s capacity in single-band over 2400 km fiber was presented.

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