Pump Laser Module for Co-propagating Raman Amplifier

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ABSTRACT The inner-grating multimode (iGM) laser, which has a new structure, has been proposed and developed as the pump laser for co-propagating Raman amplification. Among the important characteristics of co-propagating Raman amplification, we have focused on relative intensity noise (RIN) and stimulated Brillouin scattering (SBS). We have effected structural optimization and evaluation, and have devised a driving system.

1. INTRODUCTION

In the field of fiber-optic communications, increases in transmission distance and capacity have been effected using Erbium-doped fiber amplifiers (EDFAs). Recently, however, it has become essential to rely not only on EDFAs but to combine them with Raman amplification to take advantage of its characteristics. The most common type of Raman amplification currently in use relies on counter-propagation, that is, pumping light is input in the direction opposite to the signal.

However as we move to the next generation, with speeds of 40 Gbps, transmission spans of 100 km, and broader bandwidth (using L- and S-bands), the key will be to use co-propagating Raman amplification, in which pumping light is input in the same direction as the signal, at the same time as counter-propagating Raman amplification. This technology results in what is known as bi-directional Raman amplification. It has been reported that by means of multi-wavelength pumping it is possible to achieve flattening of Raman gain and broadening of bandwidth even with counter-propagating Raman amplification alone, but that without the use of co-propagating Raman amplification, flattening of the noise figure cannot be realized [1), 2)].

Here we will discuss the reasons why, in addition to the 14xx-nm laser diode modules (LDMs) widely used for EDFA pumping [3), 4)], it is necessary to develop a pump laser of the same wavelength band for co-propagating Raman amplification. The main requirements are: 1) lower relative intensity noise (RIN), 2) lower stimulated Brillouin scattering (SBS) and 3) lasing wavelength stability, and these will be addressed in turn below.

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1.1 Need for Lower Relative Intensity Noise (RIN)

RIN is an indicator of the minute changes in laser light intensity normalized by the total light intensity. In Raman amplification the lifetime of the pumping level that gives rise to gain is short (a few femtoseconds), so that the presence of noise in the pumping light will, through the amplification process, be turned directly into signal noise. In the traditional EDFA, on the other hand, the lifetime of the pumping level is comparatively long (approximately 10 msec), so that this sort of problem does not occur. In Raman amplification the gain per length is much smaller than in an EDFA, but in co-propagating Raman amplification, where the signal and pumping light propagate together in the fiber over long distances, pumping light noise is gradually superimposed onto signal noise. In a counter-propagating Raman amplifier, where the signal and pump light propagate in opposite directions, the crossover time between pumping light having a noise component and the signal is short, and the effect of pumping light noise on the signal is minimal. And since the pumping light noise is random, any effect that the signal might receive will be flattened as it proceeds in the opposite direction and not give rise to any problem. As will be understood from the above, a pump laser for

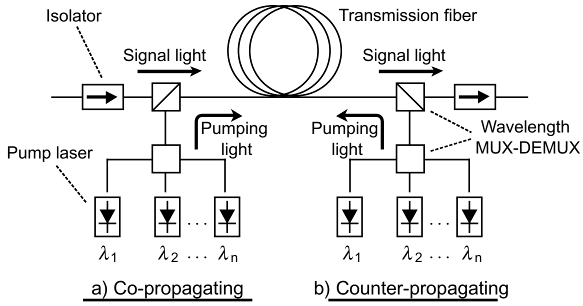

Figure 1 Basic configuration of co- and counter-propagating Raman amplifiers.

co-propagating Raman amplification must be provided with a low RIN level, such as has not been needed in the past.

1.2 Need for Lower Stimulated Brillouin Scattering (SBS)

SBS is the third-order nonlinear optical effect whereby light undergoes scattering in the reverse direction by acoustic phonons excited in the fiber by light. SBS is undesirable since, when it occurs, light is scattered in the reverse direction and makes no effective contribution to Raman amplification. In SBS there is a level of power at which this phenomenon arises--the threshold power P_{th}--which may be represented by the Equations 5)

$$P_{th}=\frac{21A_{eff}b}{GL_{eff}}\times\begin{cases}1 & (\text{if } F_p<F_b)\\ F_p/F_p & (\text{if } F_p>F_b)\end{cases} \quad (1)$$

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

$$F_b=\eta k^2\rho \quad (3)$$

Given an A_{eff} of 47 μm², L_{eff} of 55 km, α of 0.21 dB/km, which were the values for DSF used in the experiments, together with a G of 4×10^{-11} m/W and b of 2, this yields a value for P_{th} of 2.57 mW.

In the above, A_{eff} is the effective area of the fiber core; L_{eff} is the effective length of the fiber as calculated in Equation (2) using loss α and fiber length L; G is the coefficient of Brillouin gain; F_p is the linewidth of the pumping light; F_b is the width of the SBS gain band; and b is a value between 1 and 2 depending on the polarization state of the pumping light and SBS reflection light.

In Equation (3), k is $2\pi/\lambda$, ρ is fiber density, and η is a constant.

If λ is 1480 nm, F_b will be approximately 17.5 MHz. Since F_b is less than the longitudinal mode spacing of the pump laser, SBS will be generated for each of the longitudinal modes individually. The bandwidth of Raman gain, on the other hand, is wide (approximately 30 nm), so that gain from each of the longitudinal modes overlaps and the total output power of the laser contributes to gain. Accordingly if total output power is the same, the most effective way to suppress SBS without reducing Raman gain would be to increase the number of longitudinal modes and reduce the power per mode.

Looking at Equation (1) from the viewpoint of the fiber, since both stimulated Raman scattering and SBS are the third-order nonlinear optical effects, those factors that increase Raman gain, such as lower loss and reduced A_{eff}, simultaneously facilitate the generation of SBS. In fibers such as DSF, NZDSF, DCF and the like, A_{eff} is small in comparison with SMF, and SBS readily occurs.

1.3 Need for Wavelength Stabilization and Demand for a Pump Laser for Co-propagating Raman Amplification

Pumping wavelength stability is essential for designing the Raman gain profile, and the wavelength stabilization technique conventionally adopted for 14xx-nm laser diode modules was the fiber Bragg grating (FBG). In a laser diode module with FBG (FBG-LDM), the light is reflected at the FBG, which is located at a distance of several tens of centimeters, and fed back to the laser diode. This situation is referred to as coherence collapse, and is considered desirable from the standpoint of stable operation of the laser diode. However laser coherence is degraded by reflection from a point situated at a distance, so the laser linewidth becomes broader and RIN increases. Referring to Equation (1), broader linewidth is advantageous, since the threshold power for the occurrence of SBS becomes greater. Since SBS presents a problem even in counter-propagating Raman amplification, an FBG-LDM that satisfies the conditions of low SBS and wavelength stability can be used as the pump laser but an FBG-LDM with a high RIN is not suitable for co-propagating Raman amplification. To reduce RIN, it is desirable to form a grating inside the laser diode, as in a distributed feedback (DFB) laser. But the DFB laser has high coherence, generating single-mode lasing and having a narrow linewidth, so that SBS presents a problem, making it unsuitable for use as the pump laser for co-propagating Raman amplification. As can be seen from the above discussion none of the existing laser diode modules is suitable for co-propagating Raman amplification, making it necessary to develop a new pump laser.

In this paper we report on the design of a pump laser for co-propagating Raman amplification, evaluate its characteristics, and discuss the driving system.

2. STRUCTURE OF iGM LASER

The laser diode that we have developed for co-propagating Raman amplification has been designated as an inner grating multimode (iGM) laser. Its primary feature is that it does not, like the DFB laser, have a grating formed over the whole length of the laser cavity, but only over a portion, thereby achieving multimode lasing. The inner grating thereby realizes low RIN and pumping wavelength stability, and by multimode lasing realizes SBS reduction. Multimode lasing is also indispensable in reducing the degree of polarization (DOP), which is so important in Raman amplification.

The fundamental structure of the laser diode is like that of 14xx-nm laser diodes, which are of proven high output power and high reliability, with a waveguide of the buried heterostructure (BH) type. The layer structure has a strain compensation multi quantum well active layer and multistep separate-confinement heterostructure (SCH). For the purpose of Fabry-Perot mode suppression, an anti-reflection coating is applied to one of the laser diode facets.

The module structure, like conventional 14xx-nm laser diode modules, features a 14-pin butterfly package and a 2-lens coupling system. An advantage of the iGM laser is that, since the grating is inside the laser diode, the isolator can be mounted inside the laser diode module. In the FBG-LDM, by contrast, the light reflected from the FBG has to be fed back to the laser diode, so that the isolator cannot be accommodated. In configuring an amplifier, it may be that when the signal is input to the pump laser module it is reflected back into the transmission path resulting in signal noise. To avoid such a situation it is advantageous to provide the isolator inside the LDM. Providing an isolator eliminates reflected light and the light transmitted by other LDMs from entering the laser diode, thereby effecting stable operation of the pump laser.

3. FUNDAMENTAL CHARACTERISTICS OF THE iGM LASER

Figure 2 shows the light-current (L-I) characteristics of the iGM laser diode. Cavity length in 1500 μm, and an output power of 310 mW @ 1200 mA is achieved. As can be seen from the spectrum shown in Figure 3, satisfactory multimode lasing is achieved.

Figure 4 shows the current dependence of pumping wavelength. As can be seen, a good level of wavelength stability is achieved. Wavelength shift is somewhat greater than for an FBG-LDM, but is satisfactory as a pump laser for Raman amplification. The wavelength shift in the iGM laser is smaller than in the DFB laser (not shown), the result of using a longer cavity, junction-down bonding, and the excellent heat-dispersion performance obtained by means of a heat sink of high thermal conductivity. In the iGM laser, the temperature of the grating is controlled together with that of the laser diode as a whole by means of a Peltier device internal to the LDM, so that the pumping wavelength does not shift with the ambient temperature. In the FBG-LDM, on the other hand, the FBG expands and contracts with changes in ambient temperature resulting in shifts in wavelength. In the iGM laser, if the driving system is such that the greater the current input, the lower the temperature will become, it will also possible to compensate for wavelength shifts due to the driving current.

4. SBS SUPPRESSION

4.1 Relationship between SBS Suppression and Number of Longitudinal Modes [6)]

We can see from Equation (1) that there are two approaches to SBS suppression: (1) keep the light intensity of each longitudinal mode below P_{th}; or (2) broaden the linewidth and increase P_{th}.

Figure 5 shows the spectra for fiber input light and reflected light. Reflection of the same wavelength as the input light is due to Rayleigh scattering, and that of shifted wavelength is due to SBS. The reflected light due to SBS shows a shift equal to the Brillouin shift (= 11 GHz = 0.08 nm @ 1480 nm) with respect to the original light, as shown in the Equation

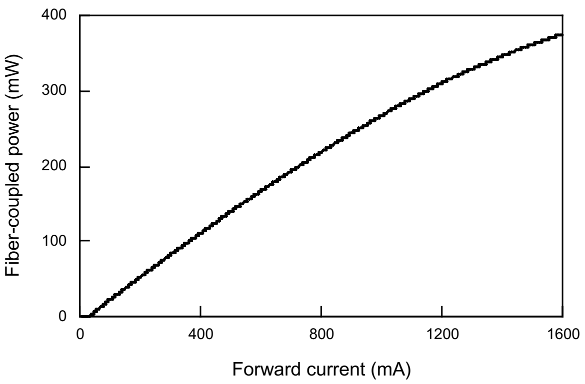

Figure 2 Light-current characteristics of iGM laser.

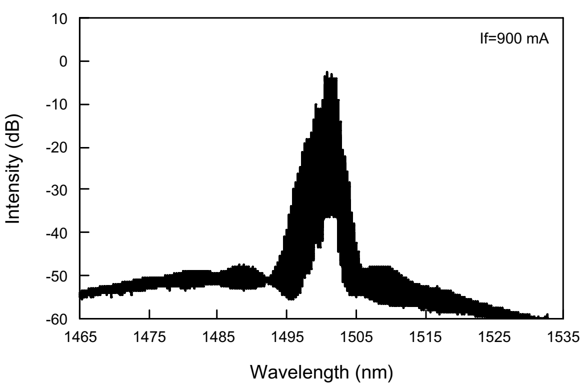

Figure 3 Spectrum of iGM laser.

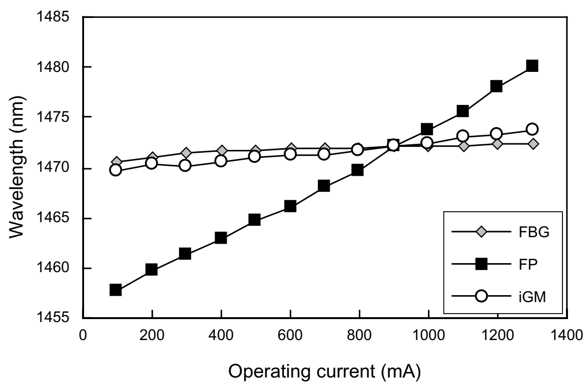

Figure 4 Current dependence of pumping wavelength.

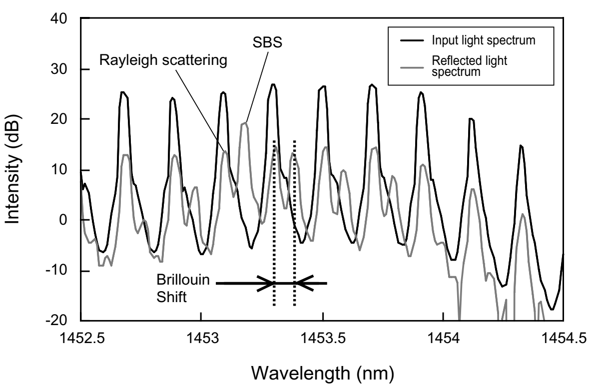

Figure 5 Spectra of fiber input light and reflected light.

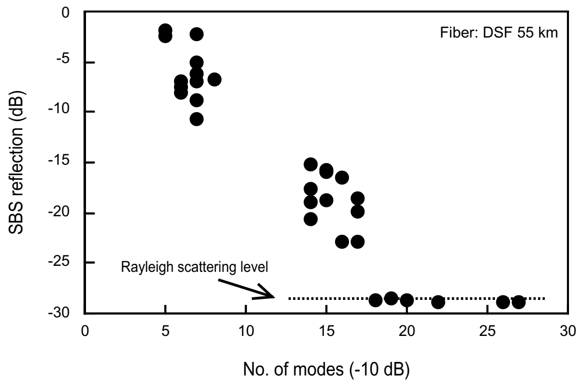

Figure 6 Relationship between number of longitudinal modes and amount of SBS reflection.

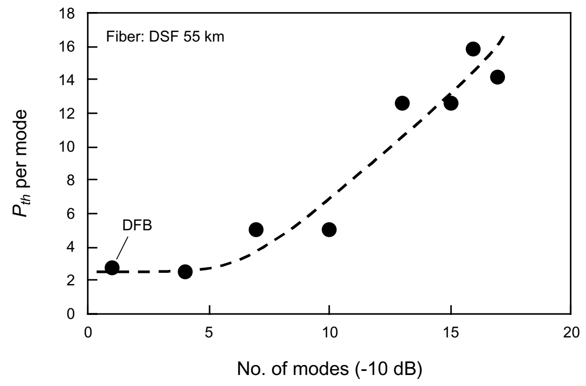

Figure 7 Relationship between number of longitudinal modes and SBS threshold power P_{th}.

$$\nu_B = 2nV_s/\lambda \tag{4}$$

where: n is the refractive index of the fiber; and V_s is the speed of sound in the fiber (5760 m/s).

We can see from Figure 5 that SBS occurs in longitudinal modes where light intensity is high, but not in those where it is low. Thus we may say with respect to approach (1) that it is effective to increase the number of modes and distribute the power among these more numerous modes.

Figure 6 shows the relationship between the number of longitudinal modes and the amount of SBS reflection. SBS is evaluated by the ratio of backward-scattered light intensity to input light intensity. Since the P_{th} for SBS is low, we have focused on the number of longitudinal modes in the region from peak to -10 dB. Looking at Figure 6 we can see that SBS is suppressed when the number of longitudinal modes is about 18 or more, and that the amount of reflection decreases to the level of Rayleigh scattering.

Figure 7 shows the relationship between the number of longitudinal modes and SBS threshold power P_{th}. Since the P_{th} in Figure 7 is the SBS threshold value occurring in each longitudinal mode individually, it should be noted that the total power being input to the fiber will be greater than that. Using a reflection spectrum similar to that shown in Figure 5, P_{th} may be found from the intensity ratio of reflected light due to SBS over each longitudinal mode. It will be understood that if the number of longitudinal modes is increased, P_{th} will be higher, suggesting that laser linewidth expands due to an increase in the number of longitudinal modes.

The point at which the number of modes is least is from data for a selected DFB laser, with a P_{th} of 2.8 mW, and this substantially agrees with an estimate from Equation (1). The other points are from data for iGM lasers, in which the number of longitudinal modes is varied by the operating current and the design of grating. In the iGM laser the number of longitudinal modes increases with an increase in the operating current, resulting in a situation in which, in the region of high operating current, SBS occurs with difficulty due to the higher number of longitudinal modes and the accompanying increase in P_{th}.

With a DFB laser, by contrast, the single-mode characteristics remains unchanged even if operating current increases, with the result that it is impossible to input to the fiber a total light power in excess of P_{th} (= 2.8 mW). If, as a result of an increase in the number of longitudinal modes, the linewidth did not vary and P_{th} remained unchanged, it would be necessary, assuming a desired input power of, say, 200 mW, to have about 80 longitudinal modes (= 200 mW/2.5 mW), but in practice this sort of situation does not occur, and is in fact impossible. Let it be noted in passing that the direct, accurate measurement of the linewidth of a multimode laser is, technically speaking, difficult.

4.2 Devising a Driving System for SBS Suppression

For any LDM and for any range of driving currents, the mere measure of increasing the number of longitudinal modes, taken by itself, is ineffective in completely suppressing SBS. If it is attempted to obtain a further increase in the number of longitudinal modes, there will be an adverse effect on wavelength stability, RIN and other characteristics. It is the authors' opinion that to eliminate SBS while maintaining the properties of the iGM laser, it is necessary to make adjustments to the method of use. In co-propagating Raman amplification there are cases in which the output power per LDM is small (say 100 mW), and in such cases it is possible to eliminate SBS by attenuating the output power outside the LDM to the point where the intensity of all the longitudinal modes is below P_{th}. In this case using a higher value of driving current will mean a greater number of longitudinal modes and the amount of attenuation required will be less.

We have also given attention to another technique known as dithering, a driving method in which a modulated signal of minute amplitude is superimposed on a DC driving current. This corresponds to approach (2) to SBS reduction. In laser diodes, internal temperature rises with the driving current causing changes in the lasing wavelength. Accordingly the use of dithering can produce minute changes in the lasing wavelength resulting in a broadening of the linewidth.

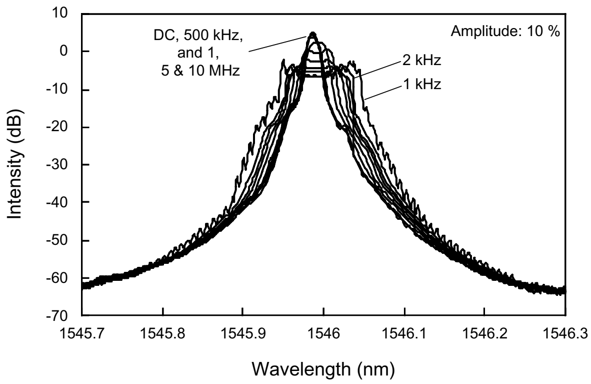

Figure 8 Broadening of DFB spectrum achieved by dithering at various frequencies.

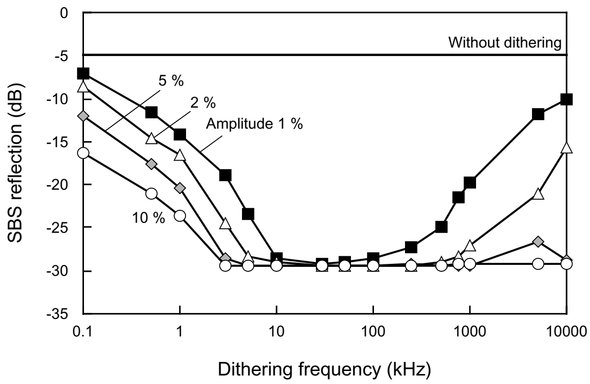

Figure 9 Change in SBS reflection due to dithering frequency.

Figure 8 shows the broadening of the DFB spectrum achieved by dithering at various frequencies using a sine wave. The dithering frequency was varied between 1 kHz and 10 MHz. The spectrum was broadest at the minimum frequency of 1 kHz, and was similarly narrow when the driving current was DC and 500 kHz or above. In the high-frequency range, laser temperature cannot respond to the changes in current produced by dithering, and increases in linewidth cease to occur. Since the carrier lifetime of a laser diode is shorter (a few nanoseconds), the light intensity modulation responds even in that range of frequencies. The spectrum when dithered using a sine wave becomes an superimposition of a Bessel function centered on the original wavelength. Since intensity of the higher mode is greater, the shape will be lower in the center as shown in Figure 8, and higher at the edges.

Figure 9 shows the change in SBS reflection due to dithering frequency and amplitude [7]. The amplitude shown in the figure is defined as the proportion between the DC component of the light and the intensity modulation component. Looking at Figure 9, it can be seen that approximately -5 dB of SBS reflection that was originally present is suppressed between frequencies of approximately 10 to 100 kHz to the Rayleigh scattering level by the small degree of modulation of only 1 %. The experiments were carried out using iGM lasers with a small number of longitudinal modes.

As can be seen from Figure 8, linewidth itself becomes greater the lower the frequency. The limit to SBS suppression on the low-frequency side is due to the fact that the SBS phenomenon responds to the changes in wavelength that are produced by dithering. SBS is produced by the interaction of forward- and backward-propagating waves, so that if, for example, the dithering frequency is too slow as compared with the time required for light to travel back and forth over the effective length of the fiber L_{eff}, the linewidth broadening that occurs will not be very effective. If, using Equation (2), an L_{eff} of 20 km is used, we will get $c/2nL_{eff}$ = 5 kHz (where c is the speed of light), which is of the same order as in Figure 9. The limit on the high-frequency side is determined, as described above, by the frequency at which linewidth ceases to broaden at the temperature response limit. It is believed that frequencies between 10 and 100 kHz that are suitable for SBS suppression will be extremely slow relative to the bit rate, and the amplitude will be small, resulting in little adverse effect on the signal.

5. EVALUATING THE RIN OF THE iGM LASER

Figure 10 plots the RIN of an iGM laser against the logarithm of frequency on the x-axis. Values for a laser diode module with an FBG and a Fabry-Perot (FP) laser without an FBG are also shown for comparison. The iGM laser achieves the low RIN values of -140 dB/Hz or less that are required for co-propagating Raman amplification over a wide range of frequencies. The FBG-LDM has peaks at intervals of $c/2nl$ corresponding to the time for the round trip over distance l to the FBG, and the RIN values are extremely high--about -120 dB/Hz. The FP laser shows increased RIN on the low-frequency side, thought to be due to the fact that it has an extremely large number of longitudinal modes resulting in mode competition.

The reason we have focused on low-frequency range RIN is that even in co-propagating Raman amplification, the velocity of propagation of the signal light and pumping light differ due to dispersion in the fiber, so that the higher frequency components of the pumping light intensity noise

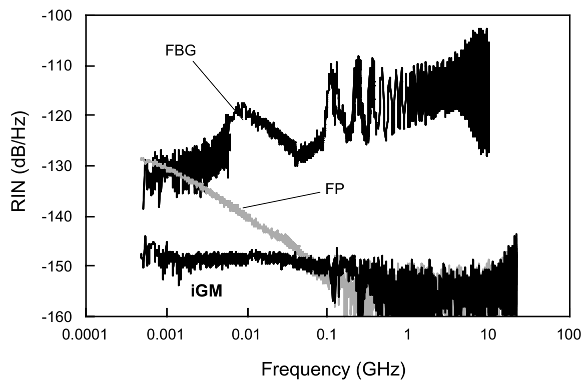

Figure 10 RIN spectra for selected types of lasers.

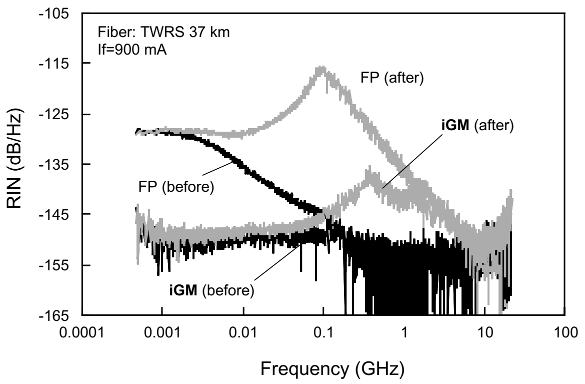

Figure 11 RIN of iGM and FP lasers before and after transmission over a 37-km TWRS fiber.

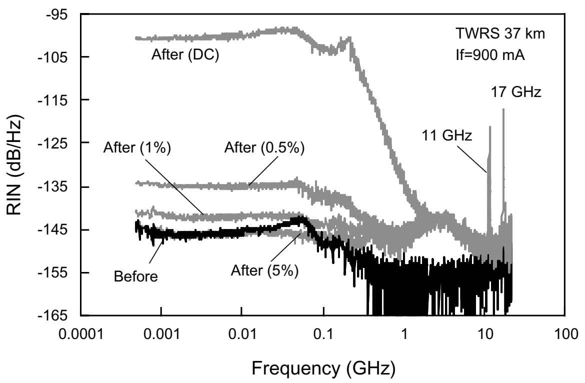

Figure 12 Increase in RIN after transmission produced by SBS and its suppression by dithering.

are averaged during transmission and have only a small effect on the signal light.

The authors have also measured a phenomenon whereby RIN increases after fiber transmission (Figure 11), which is thought to be due to mode partitioning noise (MPN) [8]. This is a phenomenon that occurs in multimode lasers, whereby the ratio in which laser gain is distributed among the longitudinal modes fluctuates over time so that the output power of each mode changes but total output power does not. At the point of input the changes due to MPN are canceled out among the various modes, but after transmission over long distances the arrival times differ under the influence of fiber dispersion so that they are not canceled out, and the total output power fluctuates. For that reason RIN is greater after transmission (gray lines) than before (black lines). In an FP laser the large number of longitudinal modes means an extraordinary increase in RIN. In an iGM too, the multimode lasing results in an increase in RIN after transmission, but about 20 dB less than the maximum values for the FP.

It was also discovered that RIN also increases as a result of the occurrence of SBS [9]. Figure 12 shows the RIN of an iGM laser before transmission (black) and after transmission (gray) at an I_f of 900 mA over a 37-km TWRS fiber. The increase in RIN is greater on the low-frequency side, and the amount of the increase is greater than that due to MPN. In experiments, the occurrence of SBS was suppressed by changing the dithering amplitude (in parentheses in Figure 12). The increase in RIN was suppressed with SBS, indicating that the phenomenon is attributable to SBS. Increases in RIN due to MPN are still seen even after SBS suppression. Since it was an iGM laser with a small number of longitudinal modes, such that SBS would occur, that was used in the experiments, the increase in RIN due to MPN was smaller than that of the iGM laser in Figure 11. Furthermore in the increase in RIN due to MPN a peak was seen, whereas when due to SBS, no peak was seen in the frequency range observed, and there was a tendency to increase the lower the frequency.

When SBS occurred, two sharp peaks were observed in the high-frequency region. These were determined, respectively, by the difference in frequency between the longitudinal mode giving rise to SBS and the SBS light (that is to say, by the Brillouin shift, approximately 11 GHz), and by the difference in frequency between the single longest-wavelength longitudinal mode giving rise to SBS and the SBS light (approximately 17 GHz).

Since the DFB is a single-mode laser, there is no increase in RIN due to MPN even after transmission but since SBS occurs readily, an increase in RIN due to SBS is observed. In the FP laser, as can also be seen in Figure 4, the wavelength shifts due to operating current are large, but consideration is being given to using them in co-propagating Raman amplification by stabilizing the wavelength by constant current drive and varying the output power using a variable optical attenuator (VOA). Nevertheless, as has been described above, the RIN of the FP laser increases in the low-frequency range or after transmission, raising concerns about the effect they would exert when used in co-propagating Raman amplification. The FP lases in a large number of longitudinal modes, but SBS is not suppressed in all of them, and still occurs in some.

6. CONCLUSION

A new type of laser has been developed as a pump laser for co-propagating Raman amplification, having an inner grating and known as the iGM. It has been shown that SBS can be reduced through the use of multimode lasing and dithering. In comparison with other types of laser, there are major problems of RIN in the FBG-LDM, wavelength stabilization in the FP, and SBS in the DFB. More detailed investigation of RIN showed that increases occurred in the FP in the low-frequency range and after fiber transmission, and in the DFB after transmission when SBS occurred, so that, taken overall, the noise characteristics of the iGM were superior. The above leads us to conclude that the iGM is the most suitable to use as a pump laser in co-propagating Raman amplification.

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