Development of a Crystal-Type Depolarizer

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ABSTRACT Fiber Raman amplifier (hereafter called Raman amplifier) is becoming popular for its superiority in characteristics. Because the Raman amplifier has a large polarization dependence of Raman gain, a number of designs are being proposed to reduce the influence, and a device known as depolarizer plays an important role among those designs. A depolarizer based on a 45° spliced polarization-maintaining fiber (PMF) is already in practical application. However, this depolarizer has problems such as, besides the necessity for large accommodation space, unsteady Raman gain due to the deterioration of degree of polarization (DOP), which is caused by temperature fluctuations in the amplifier. Accordingly, the authors have developed a crystal-type depolarizer recently, and succeeded in realizing miniaturization of the device as well as reduction of the temperature dependence of DOP. It is expected that this development help to promote popularization of Raman amplifiers as well as demand increase hereafter.

1. FUNCTION OF DEPOLARIZER

Depolarizer is an optical device that can convert, as illustrated in Figure 1, any incident light that is completely or partially polarized into unplorized light.

When the end point of its electric field vector represents with respect to time a line, a circle, or an ellipse, then the light is defined as completely polarized.

Unpolarized light is comprised of an even distribution of all sorts of polarized light, and partially polarized light refers to a mixture of the completely polarized light and the unpolarized light.

DOP is used to represent the light amount ratio of completely polarized light of certain light with respect to its total light amount. Therefore, the DOP for completely polarized light and unpolarized light are 100 % and 0 %, respectively, and the DOP for partially polarized light ranges between 0 % and 100 %.

2. PROBLEMS WITH CONVENTIONAL TECHNOLOGIES

Depolarizers for optical communications based on PMF are already in practical application. In this technology, an all-fiber depolarizer of Lyot-type is extensively used [1), 2)], in which two lengths of PMF with a ratio of 1:2 in length are spliced together to have a 45° between the polarization axes of the fibers.

But the all-fiber depolarizer of Lyot-type has two problems: one is deterioration in DOP due to temperature changes and the other is related with accommodation space.

The deterioration of DOP due to temperature changes is probably caused by the changes in the state of polarization of the light that is incident on the depolarizer under the influence of temperature changes in the amplifier. Figure 2 shows the DOP changes in a conventional depolarizer when the temperature is changed between -10°C and 70°C. It is seen that the DOP changes between 4 % and 15 % maximum.

With regard to accommodation space, irrespective of the increasing requirement for saving of the space to promote size reduction of amplifiers, all-fiber depolarizers need a large accommodation space since they use a fiber as long as more than 20 m, which is subject to allowable bending radius. When a heat-insulating package is used to decrease the temperature changes in DOP, space saving becomes more difficult.

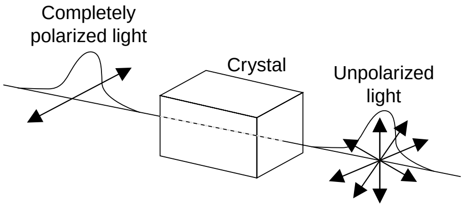

Figure 1 Schematic of depolarizer.

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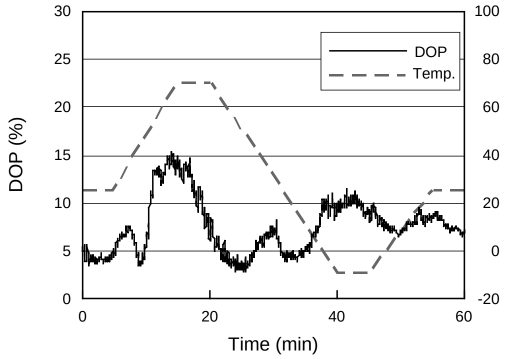

Figure 2 Temperature dependence of DOP of conventional depolarizer.

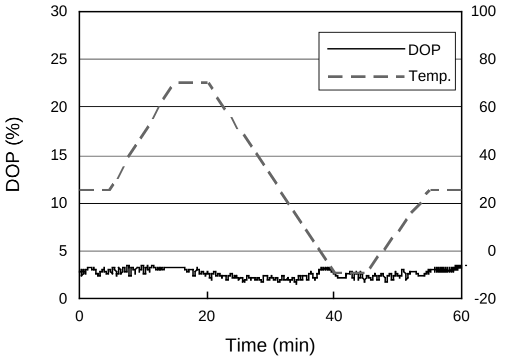

Figure 3 Temperature dependence of DOP of a depolarizer equipped with polarizer.

Table 1 Target characteristics of depolarizer.

	Min.	Max.	Unit	Remarks
Operating temperature	-10	70	°C	
Operating humidity	0	85	%RH	
Insertion loss		0.80	dB	@T_{op}
DOP		7	%	@T_{op}
Return loss	50		dB	@T_{op}
Package dimension	ϕ5.5×60		mm	

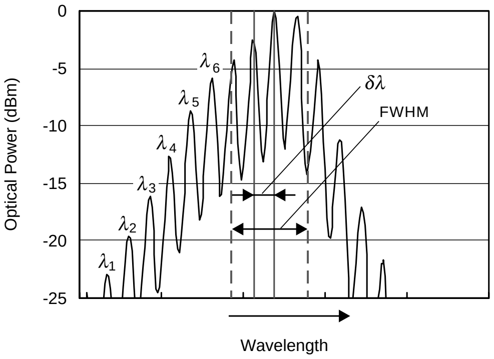

Figure 4 Output spectrum of pumping laser diode.

3. FEATURES OF DEVELOPED PRODUCT AND TARGET CHARACTERISTICS

The depolarizer developed this time has the following features to solve the problems mentioned above.

With respect to DOP deterioration, the depolarizer was designed to provide a polarizer in front of a birefringent crystal to stabilize the state of polarization of the incident light, aiming at a significant reduction in the deterioration of DOP.

With regard to accommodation space, a birefringent crystal was used in the design since a significant space saving by all-fiber depolarizers was found to be difficult. Moreover, through optimization of the length of the birefringent crystal, the accommodation space was successfully reduced to about one tenth of that for conventional depolarizers.

Table 1 shows the target characteristics of this development program.

The upper limit of DOP was set to a value such that the polarization dependence of Raman gain (PDRG) became equivalent to or less than the polarization dependent loss (PDL) of general optical components[3].

4. DESIGN

4.1 Design for Reduction of DOP Deterioration

The DOP deterioration of a depolarizer is caused by the changes in the state of polarization of the light incident on the birefringent crystal, so that the temperature change in an amplifier is the main cause of deterioration after the depolarizer is assembled into the amplifier. Consequently, it is possible to reduce the DOP deterioration by inserting a polarizer in front of the birefringent crystal thereby stabilizing the state of polarization of the incident light.

Figure 3 shows the temperature dependence of DOP when a polarizer is inserted in front of the birefringent crystal. By comparing Figure 3 with Figure 2, it can be seen that whereas the DOP without polarizer changes up to 15 %, the DOP with polarizer changes by about 2 %, and the maximum DOP is 4 % or less.

4.2 Design for Saving of Accommodation Space

Basically it is very difficult to design a low-attenuation, as well as compact depolarizer maintaining its ability of converting any polarized light into unpolarized light. However, in the case of a depolarizer for pumping lasers, it is possible to make the depolarizer low in attenuation and compact in size taking advantage of the features of pumping lasers.

The output light of a Fabry-Perot laser diode has, as shown in Figure 4, the following features:

a) Completely linear polarized light
b) Multiple intensity peaks with a period of FP-mode interval, i.e.,$\delta\lambda$
c) Full width half maximum (FWHM) of intensity distribution is around 1 nm

Thus from the feature a), it is understood that every wavelength component in the wavelength spectrum of the pumping light traces, since the laser output undergoes phase differences when passing through the birefringent crystal, a great circle on the Poincare sphere as the phase difference changes.

Taking the feature b) into consideration further, polarization vectors which are weighted by the light intensity of the adjacent peaks in the pumping light are summed, if a birefringent crystal is provided to give a phase difference of $(2m+1)\pi$ between the adjacent FP-mode peaks, so that the totality of the vectors become minimum as illustrated in Figure 5 using the Stokes space. When this procedure is repeated over the entire wavelengths, the sum of the vectors approaches the zero, resulting in DOP decrease.

Below will be presented the design taking advantage of the features of the pumping laser diode. First, the design using features a) and b) will be described.

The phase change $\Gamma(\lambda)$ of certain light (wavelength is λ) after passing through a birefringent crystal can be expressed, if the refractive index difference of crystal be Δn and the length be L, by the equation (1).

$$\Gamma(\lambda) = 2\pi L \Delta n / \lambda \tag{1}$$

Thus the length of crystal that gives a phase difference of $(2m+1)\pi$ between the adjacent peaks after passing through the crystal can be obtained from equation (2).

$$\Gamma(\lambda) - \Gamma(\lambda+\delta\lambda) = (2m+1)\pi \tag{2}$$

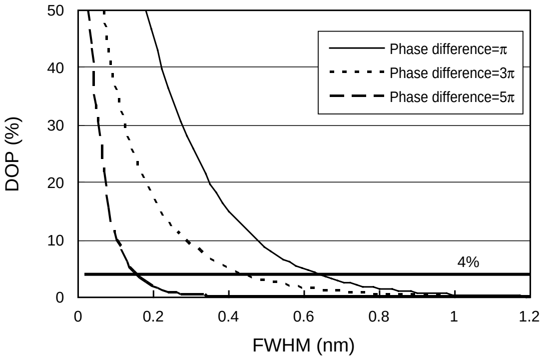

Figure 7 **Relationship between FWHM and DOP with phase difference as a parameter.**

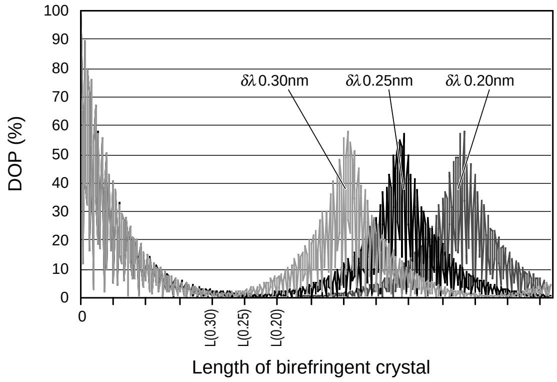

Figure 8 **Relationship between birefringent crystal length and DOP for various pumping lasers suggesting crystal length optimization.**

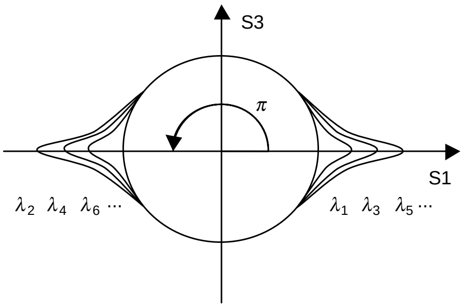

Figure 5 **DOP reduction represented in the Stokes space.**

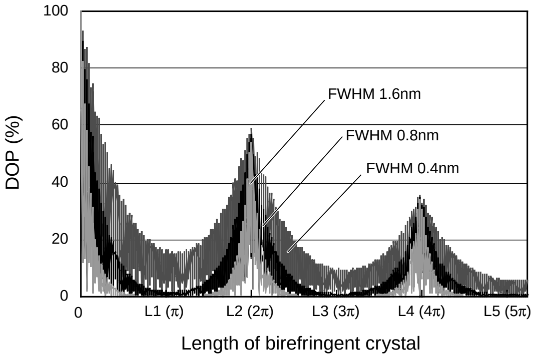

Figure 6 **Relationship between birefringent crystal length and DOP with FWHM as a parameter.**

Figure 6 shows the relationship between the length of birefringent crystal and the DOP. It can be confirmed that the DOP takes a local minimal value at every phase difference of $(2m+1)\pi$ and that the DOP becomes smaller the larger the phase difference, i.e., the order m.

Next will be described the design that exploits the feature c). Figure 7 shows the relationship between the FWHM of light intensity and the DOP, from which it can be confirmed that, in the case of a pumping laser with a FWHM value of about 1 nm, a sufficiently small DOP can be obtained even at a small phase difference of π. The length of birefringent crystal to give such a phase difference can be calculated by equation (2) by letting m be 0, and referring to Figure 6, the length turns out to be the smallest to result in a local minimal of DOP.

4.3 Design Customization

By means of the design procedures described above, it is now possible to optimize the depolarizer design to make it suitable for various pumping lasers with different $\delta\lambda$ and FWHM values.

As an example, the relationships between the DOP and birefringent crystal length for three pumping lasers with a FWHM value of 0.8 nm and $\delta\lambda$ of 0.20 nm, 0.25 nm, and 0.30 nm are calculated and the results are shown in Figure 8. It can be seen from the figure that the length of birefringent crystal can be optimized to deal with pumping lasers of different characteristics, and that the length has to be optimized in order to implement high-performance pumping light sources.

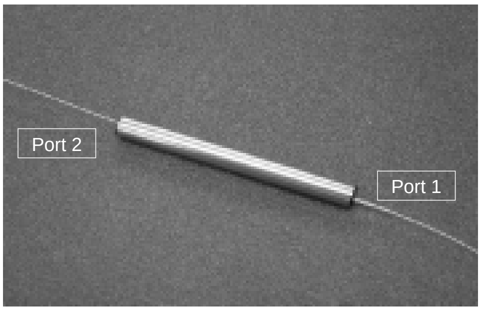

Figure 9 Appearance of depolarizer module.

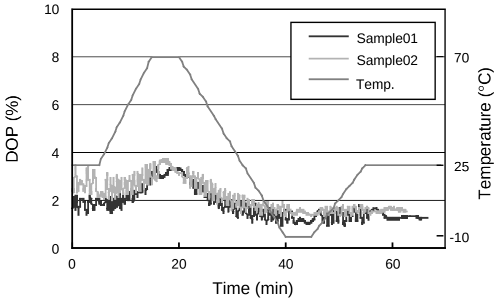

Figure 10 Temperature dependence of DOP of prototype depolarizer.

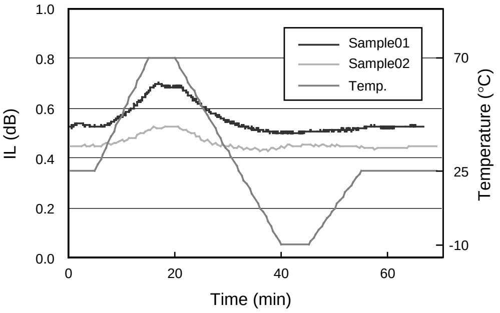

Figure 11 Temperature dependence of insertion loss of prototype depolarizer.

5. DEVICE STRUCTURE

Figure 9 shows an appearance of the developed depolarizer module. The outer diameter is 5.5 mm and the length 60 mm, achieving the targeted miniaturization. The device structure is such that the pumping light of complete polarization incident on the port 1 with a PMF passes through a polarizer and a birefringent crystal, and subsequently exits as unpolarized light from the port 2 with a single mode fiber (SMF).

6. DEVICE CHARACTERISTICS

Below will be described the optical characteristics of the prototype module.

Figures 10 and 11 show the temperature dependence of DOP and insertion loss of the module, respectively. Using a pumping laser whose characteristics are shown in Figure 12, good performance characteristics were achieved, in the -10~+70°C temperature range, such as DOP≤4 %, DOP fluctuations≤2 %, and insertion loss≤0.8 dB. Table 2 summarizes typical performance of the developed product.

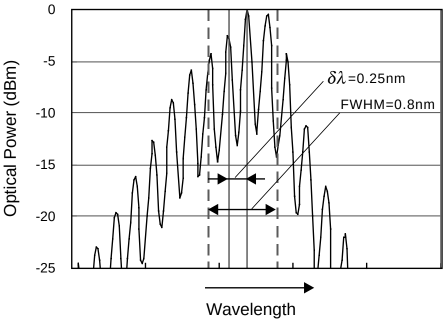

Figure 12 Output spectrum of pumping laser diode used in prototype module.

Table 2 Characteristics of developed depolarizer.

	Min.	Max.	Typ.	Unit	Remarks
Operating temperature	-10	70		°C	
Operating humidity	0	85		%RH	
Insertion loss		0.80	0.50	dB	@T_{op}
DOP		7	4	%	@T_{op}
Return loss	50		55	dB	@T_{op}
Package dimension	ϕ5.5×60			mm	

7. IN CONCLUSION

We have developed a depolarizer --an essential device for Raman amplifiers, which are expected to enjoy an increasing demand in future. By designing a new structure that take advantage of the features of pumping lasers for the amplifiers, we have achieved a goal of realizing a crystal-type depolarizer with a significant size reduction and excellent DOP characteristics than ever before.

In particular, the temperature dependence of DOP has been improved to 4 % or less over the entire temperature range. It is hoped that the developed product is extensively used in future thereby satisfying the stringent requirements for gain performance of Raman amplifiers as the capacity in optical communications is enhanced.

REFERENCES

1) K.Bohm et al.: Performance of Lyot Depolarizers with Birefringent Single-Mode Fibers, J of Lightwave Tech., LT-1, 71-74(1983)
2) S.Matsushita et al.: Design of Temperature Insensitive Depolarizer for Raman Pump Laser Diode, OFC2002, WB3(2002)
3) Y.Emori et al.: Cost-effective depolarized diode pump unit designed for C-band flat-gain Raman amplifiers to control EDFA gain profile, OFC2000, FF4(2000)