

Characterization of wavelength dependent birefringence inside the ring type fiber cavity using the polarization dependence of laser outputs

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Using the polarization dependence of laser output powers, we measured the characteristics of the birefringence, such as the magnitude of phase retardation, the ellipticity, and the off axis angle to the fiber optical axis, inside the ring type fiber laser cavity.

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I. INTRODUCTION

From about 10 years ago, many researches have focused on the multi-wavelength light communication systems all over the world. Multi-wavelength light communication systems use the technology of transmitting several wavelength light signals with high bit rates in a single fiber, and require the good characteristics of high frequency light transmission through the fiber in the operating wavelength band. The group velocity difference between polarization modes which makes the signal distortion of the transmitted light signals is a significant characteristic for light transmission in the high frequency (beyond 100 GHz) range. This group velocity difference, or polarization mode dispersion, mainly results from the birefringence inside the fiber. The birefringence inside the fiber has been investigated for many years, and several measurement methods have been reported. [1]- [4]

The birefringence is characterized by three parameters : the total phase retardation between polarization modes ("δ"), the ellipticity between circular and linear birefringence ("B"), and the off-axis angle to the fiber axis ("A"). [5] Direct measurements of these parameters by transmitting polarized light through the fiber were known to be inaccurate and dependent on the quality of the measurement tools.

Ring type fiber lasers have been widely used for such applications as the wavelength tunable laser, ultra short mode-locked laser, and soliton light sources. [5]- [7] The polarization characteristics of the laser output from the ring fiber cavity are determined directly by the birefringence inside the laser cavity without other

transformations. [5,8] Therefore, by observing the polarization dependence of the ring fiber laser output and comparing it with theoretical predictions, the parameters of birefringence can be measured.

In this paper, we reported the measured results of the birefringence characteristics by using the polarization dependence of laser output power in the ring type fiber cavity. We designed the fiber ring laser cavity with collimator and quarter wave plate to measure the parameters of the birefringence inside the laser cavity. When the orientation angle of the quarter wave plate changes, the polarization eigenmodes of the ring fiber laser and their gain through one round trip of the ring fiber cavity are changed by the resultant birefringence including the polarization evolution of the quarter wave plate. If one polarization mode is selected with the wavelength filter and the polarizer inside cavity, the laser output power measured as a function of the quarter wave plate orientation angle is proportional to the gain of single polarization eigenmode through the fiber cavity. From the variation pattern of the measured gains strongly depending on the birefringence inside the fiber cavity, the parameters of resultant birefringence through the ring type fiber cavity including nonlinear polarization can be obtained.

When the circular polarizer for selecting the circular polarization eigenmode was used, the variation patterns of the gain for the variation of the quarter wave plate orientation angle had simple sinusoidal functions with 180° periodicities. Their phases were determined by the off axis angle, and their amplitudes were determined by the phase retardation and the ellipticity

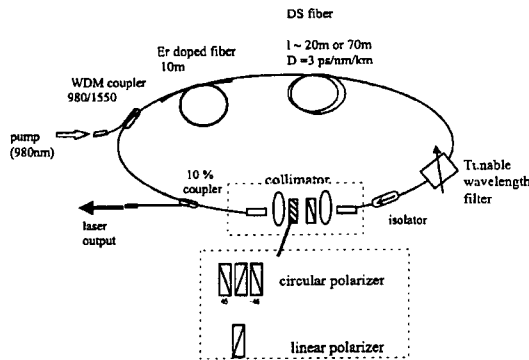


FIG. 1. Schematic diagram of a ring type fiber laser with the collimator set.

angle of the birefringence. Thus, the parameters were easily obtained, but the angle ambiguity existed. When the linear polarizer for selecting the linear polarization mode was used, the special patterns of the gain were uniquely characterized by the phase retardation, the ellipticity angle, and the off axis angle of the birefringence. Because the patterns were sensitive to each parameter, the parameters were accurately obtained from measured patterns of the laser power for the variation of the quarter wave plate angle. The average errors in measurements could be about 5° , independent of the polarization state of the output port.

In section II, the theoretical modeling is presented. Section III describes the measured results. The summary of this paper is in section IV.

II. THEORETICAL MODELS

We made theoretical models using Jones mathematics.

We considered the ring type fiber cavity as shown in Fig. 1. It was assumed that the components, such as the collimator, an isolator, and fiber couplers, were completely polarization insensitive and that non-linear phenomena in the fiber cavity were negligibly small. The components with polarization evolution were Er doped fiber, dispersion shifted fiber (DSF), and quarterwave plate. Er doped fiber was made to have little intrinsic birefringence below $0.01^\circ/\text{m}$, but might have pump induced refractive index changes. [9,10] DSF was found to have the wave-dependent birefringence, as measured with polarization analyzer. The total birefringence through Er fiber and DSF can be characterized by three parameters: the magnitude of the phase retardation, $\delta (= \sqrt{\alpha^2 + \beta^2}l)$, the ellipticity parameter, $B (= [\tan^{-1}(\alpha/\beta)]/2)$, and the azimuth angle to the fast axis of the fiber, A , where α is the circular birefringence and β is the linear birefringence. [5] The quarter wave-plate was wavelength independent and could be rotatable about the fiber axis with the orientation angle, denoted by " θ ".

1. When a circular polarizer is used

Jones matrix for the polarization evolution through one round trip of the designed cavity, O , can be expressed as

$$O = \begin{bmatrix} (a - ci)(1 + i \cos 2\theta - \sin 2\theta) & i(a - ci)(1 - i \cos 2\theta + \sin 2\theta) \\ -i(b + di)(1 + i \cos 2\theta - \sin 2\theta) & (b + di)(1 - i \cos 2\theta + \sin 2\theta) \end{bmatrix} / 2\sqrt{2}, \quad (1)$$

where $a = \cos \delta/2 + i \sin \delta/2 \cos 2B \cos 2A$, $b = \cos \delta/2 - i \sin \delta/2 \cos 2B \cos 2A$, $c = \sin 2B \sin \delta/2 + i \sin \delta/2 \cos 2B \cos 2A$, and $d = -\sin 2B \sin \delta/2 + i \sin \delta/2 \cos 2B \cos 2A$. [5,8]

After straightforward calculations from the eigenvalue equation of matrix, O , the eigenvalues can be obtained as,

$$\lambda_1 = (a + b - ci + di + (ai - bi + c + d) \cos 2\theta + (-a + b + ci + di) \sin 2\theta) / 2\sqrt{2}, \quad \lambda_2 = 0.0, \quad (2)$$

From this Eq., the normalized gain of a single polarization mode through the fiber cavity is a function of parameters of the birefringence and θ , as follows ;

$$g = (1 + 2 \sin \delta/2 \cos 2B \cos(2\theta - 2A + \eta)) / 2, \quad (3)$$

where $\eta = \tan^{-1}(\tan \delta/2 \sin 2B)$.

The gain shows a sinusoidal function of θ with 180° periodicity, as shown in Fig. 2. The phase retardation and the ellipticity of birefringence determine mainly the amplitude of the gain pattern for the variation of the quarter wave plate orientation angle and the off axis angle determines only its phase. When the bire-

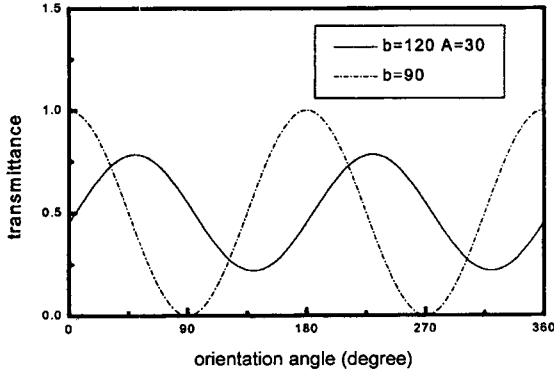


FIG. 2. Gains of the ring fiber laser with circular polarizer as a function of quarterwave plate orientation angle.(theoretical results). Solid line is for a ring fiber cavity with parameters $\delta=120^\circ$, $A=0.0$, and $B=0.0$. Dashed line is for a ring fiber cavity with parmeters $\delta=90^\circ$, $A=0.0$, and $B=0.0$.

fringence is linear, the amplitude of the gain has a function of only the phase retardation, ' δ ', and the phase of the gain is identical to twice the off axis angle, A .

2. When a linear polarizer is used

Similarly, the normalized gain of a single polarization mode through the fiber cavity can be obtained as following

$$g = (2 + e + f \sin 2\theta + e \cos 4\theta + h \sin 4\theta)/4, \quad (4)$$

where $e = \cos^2 \delta/2 + \sin^2 \delta/2 \cos^2 2B \cos^2 2A - \sin^2 \delta/2 \cos^2 2B \sin^2 2A - \sin^2 \delta/2 \sin^2 2B$, $f = -4 \cos 2B \sin \delta/2 (\sin 2B \sin \delta/2 \cos 2A - \cos \delta/2 \sin 2A)$, and $h = 2 \sin \delta/2 (\cos^2 2B \cos 2A \sin 2A \sin \delta/2 + \cos \delta/2 \sin 2B)$.

The gain is a complicated function of θ and the parameters of birefringence, B , δ , A . When the birefringence is linear ($B = 0.0$) and aligned to the fiber

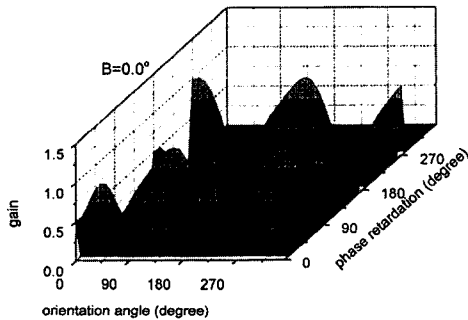


FIG. 3. Gains of the ring fiber laser with linear polarizer as a function of quarterwave plate orientation angle and phase retardation of birefringence.(theoretical results, $B=0.0$, $A=0.0$).

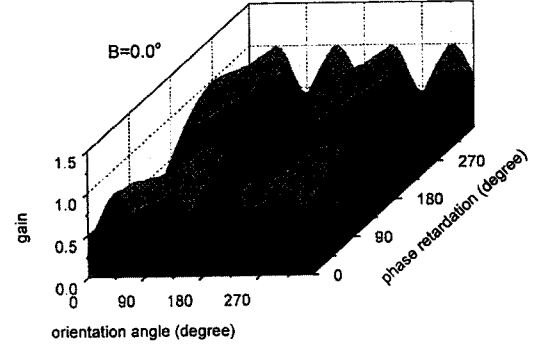


FIG. 4. Gains of the ring fiber laser with linear polarizer as a function of quarterwave plate orientation angle.($\delta=0.0^\circ$, 90° , 180° , 270° , $B=0.0$, $A=0.0$).

axis ($A = 0.0$), the simulated results in Figs. 3 and 4 show the dependence of the gain on the magnitude, δ . When $\delta = n\pi$ (see Fig. 4), the gain has simple sinusoidal function with 90° periodicity and 0.5 amplitude for the variation of quarter wave plate angle(see Fig.4). When $\delta = (2n + 1)\pi/2$, the period and the modulation amplitude become double values, i.e. 180° and 1.0, respectively (see Fig.4). The widths of peaks and amplitudes of oscillation pattern make it possible for the magnitudes of the phase retardation to be measured. The changes of off-axis angle, A , make the gain pattern change sensitively, as shown in Fig. 5.

When the birefringence is purely circular ($B= 45^\circ$), the gain has simple form as follows ;

$$g = (2 + \cos \delta + \cos(4\theta + \delta))/4. \quad (5)$$

In this case, the modulation amplitude and period of the gain remain constant, and the initial phase and the reference level are shifted in accordance with the

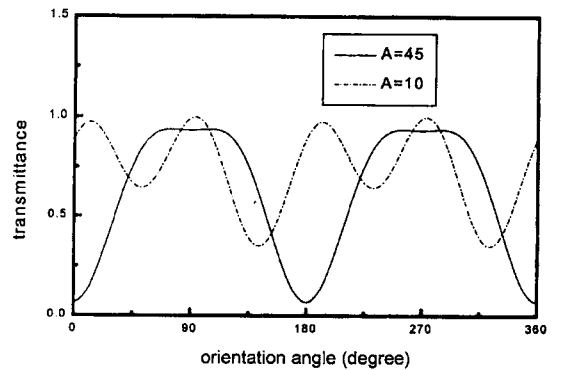


FIG. 5. Gains of the ring fiber laser with linear polarizer as a function of quarterwave plate orientation angle. Solid line is for a ring fiber cavity with parameters $\delta=60^\circ$, $A=10.0$, and $B=0.0$. Dashed line is for a ring fiber cavity with parmeters $\delta=60^\circ$, $A=45.0$, and $B=0.0$.

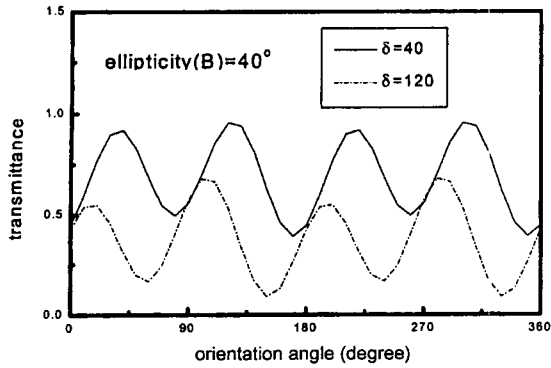


FIG. 6. Gains of the ring fiber laser with linear polarizer as a function of quarterwave plate orientation angle. Solid line is for a ring fiber cavity with parameters $\delta=40^\circ$, $A=0.0$, and $B=45.0$. Heavy solid line is for a ring fiber cavity with parameters $\delta=60^\circ$, $A=0.0$, and $B=45.0$. Dashed line is for a ring fiber cavity with parameters $\delta=120^\circ$, $A=0.0$, and $B=45.0$.

magnitude of phase retardations, as shown in Fig. 6. However, the information of the off axis angle cannot be obtained in this case.

III. MEASURED RESULTS

Ring type Er doped fiber lasers were constructed as shown in Fig. 1. A 10 m long Er doped fiber with doping rate of 450 ppm (manufactured by AT&T) and a 20 m long (or 70m) dispersion shifted fiber (DSF) with 3.5 ps/nmkm dispersion at 1550 nm were used for the laser cavity. The Er doped fiber had negligibly smaller Polarization Mode Dispersion than 0.002 ps/nmkm at the wavelengths between 1500nm and 1600nm. The DSF had wavelength dependent birefringence which was measured with polarization analyzer HP 8509B, as shown in Fig 7. However, these data were only the magnitudes of the phase retardations, δ , and the other

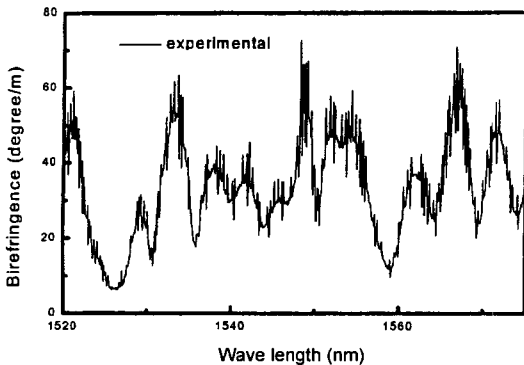


FIG. 7. Wavelength dependence of the intrinsic birefringence inside the dispersion shifted fiber.

parameters, 'B' and 'A', could not be measured accurately with this equipment (polarization analyzer) for the fabricated fiber cavity. A 980 nm pumping laser was used with a wavelength multiplexing coupler. Laser output was taken from one port of the fiber coupler with 10 % coupling ratio. A polarization insensitive isolator was installed to operate at one-direction. A tunable wavelength filter with 0.7 nm spectral bandwidth was set to select the laser wavelength, next to the isolator. A collimator set from Oz Optics was installed in front of the output coupler. The collimator could contain two subsets between the collimating lenses. One subset was only a quarter wave plate with the rotatable angle positioner to investigate the polarization dependence of laser output. Another one was for selecting a polarization eigenmode. To select a circular polarization eigenmode, a linear polarizer and two quarter wave plates with 45° and -45° off axis angle referenced to the optical axis of the polarizer, were installed in the role of a circular polarizer, in front of the quarter wave plate for investigation. For selecting the linear polarization mode, only a linear polarizer was installed.

1. When the circular polarization eigenmode was selected

The optical powers of the ring type fiber laser at 1528.8 nm and 1530.4 nm with 30 mW pump power were measured by the optical power meter, as shown in Figs. 8 and 9, respectively. They showed the sinusoidal function with 180° periodicity as theoretically predicted. The amplitudes of gain modulation for the angle variation of the quarterwave plate were 0.8 and 0.7, respectively. The theoretically predicted gains with parameters of $\delta=473^\circ$ and $B=0.0$ and $A=350^\circ$

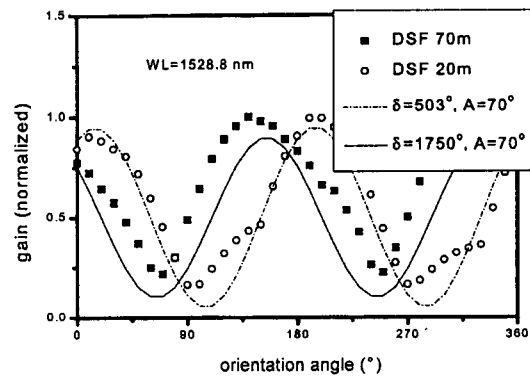


FIG. 8. Fiber laser powers (empty boxed curve and asteric dotted curve) and theoretical gains (solid line curves) with circular polarizer as functions of the quarter-wave plate orientation angle at 30 mW pump power and 1528.8 nm.

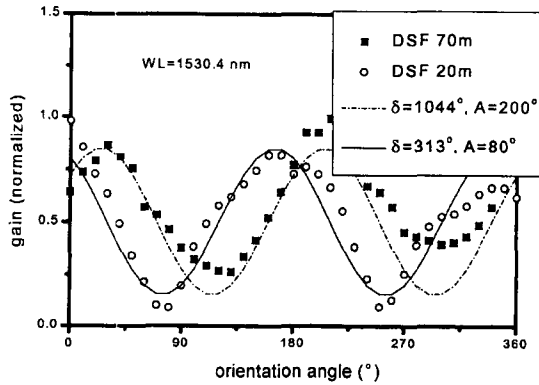


FIG. 9. Fiber laser powers (cross dotted curve and asteric dotted curve) and theoretical gains (solid line curve and dashed line curve) with circular polarizer as functions of the quarter-wave plate orientation angle at 30 mW pump power and 1530.4 nm.

at 1528.8 nm and with $\delta=313^\circ$ and $B=0.0$ and $A=80^\circ$ at 1530.4 nm, as shown in solid line curves of Figs. 8 and 9, respectively, agreed well with the measured laser powers. This agreement said that the patterns of normalized optical powers were nearly the same as the ones of normalized gains. The phase and the amplitude of optical power modulation for the angle variation of the quarter wave plate gave the information of the birefringence inside the ring fiber cavity. Assuming that the birefringence was linear, the parameters of the birefringences at several wavelengths could be obtained from the patterns of measured laser powers, as shown in the table 1. With respect to the 360° angle ambiguity, the values of phase retardations were adjusted into the ranges which were predicted by the measured values of DSF with polarization analyzer before the fabrication of the fiber cavity. These ambiguity with 360° periodicity can be removed by measuring the parameters for the variation of the fiber cavity lengths.

The measured phase retardations of birefringences

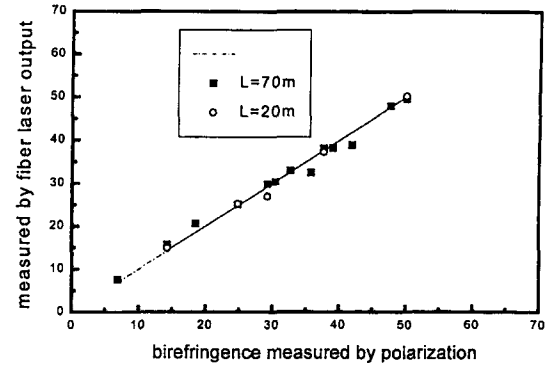


FIG. 10. Comparison of the measured birefringence with the present method with the measured ones with polarization analyzer. Cross dotted curve was for fiber cavity with the 70 m DSF and empty square dotted curve was for fiber cavity with the 20 m DSF.

with this method coincided well with the ones with the polarization analyzer, as shown in Fig. 10, which said that the assumption about the linearity of the birefringence was reasonable. In addition to this accuracy, this method gave information about the off axis angle, 'A'. The off axis angles of the birefringence to the fiber axis at the given wavelengths were found to be random. However, the ellipticity angle mixed with the phase retardations remained uncertain.

2. When the linear polarization eigenmode was selected

The optical powers of the ring type fiber laser at 1528.8 nm and 1532.5 nm with 44 mW pump power were measured by the optical power meter, as shown in Figs. 11 and 12, respectively. The laser powers at 1528.8 nm as in Fig. 11, oscillated with 180° periodicity and about 0.8 amplitude, but the laser powers at 1532.5 nm as in Fig. 12 oscillated with 90° periodicity and alternative amplitudes of 0.3 and 0.5. The theoret-

TABLE 1. Measured parameters of birefringence inside the ring fiber cavity with circular polarizer. * from measured data with polarization analyzer.

Wave-length(nm)	Parameters (20m DSF)			Phase retardation through DSF*	Parameters (70m DSF)			Phase retardation through DSF *
	δ	A	B		δ	A	B	
1525.3	152	110	0.0	138				
1528.8	473	350	0.0	496	1750	350	0.0	1764
1530.4	313	170	0.0	286	1044	200	0.0	1043
1531.8	763	80	0.0	752	2610	80	0.0	2632
1533.8	990	160	0.0	1000	3510	160	0.0	3500
1535.8	412	60	0.0	370				
1545.9	598	170	0.0	584	1890	150	0.0	2044
1551.2	758	170	0.0	952				

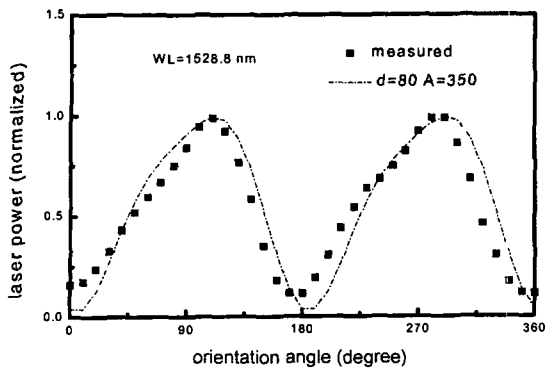


FIG. 11. Fiber laser powers (empty boxed curve) and theoretical gains (solid line curve) with linear polarizer as functions of the quarter-wave plate orientation angle at 44 mW pump power and 1528.8 nm.

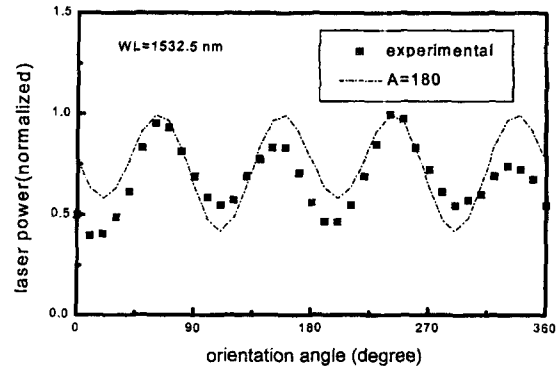


FIG. 12. Fiber laser powers (filled square curve) and theoretical gains (solid line curve) with linear polarizer as functions of the quarter-wave plate orientation angle at 44 mW pump power and 1532.5 nm.

tically predicted gains with parameters of $\delta=440^\circ$ and $B \sim 0.0$ and $A=20^\circ$ at 1528.8 nm and with $\delta=710^\circ$ and $B \sim 0.0$ and $A=180^\circ$ at 1532.5 nm, as shown in solid line curves of Figs. 11 and 12, respectively, agreed well with the measured laser powers. This method took more tedious work to obtain the parameters from measured data than the method with a circular polarizer. However, it could give more accurate information about the parameters of the birefringence because the patterns changed very sensitively with the parameters of the birefringence. By measuring and comparing the patterns of laser power with those of theoretical gain, the parameters of the birefringence at several wavelengths with pump powers of 44mW and 100mW could be obtained, as shown in table 2. Measured results showed that the birefringences were almost linear.

In the last column of table 2, are the phase retardations through only the DSF, which were measured with polarization analyzer before the fabrication of the fiber cavity. The differences between the phase retar-

ations inside the fiber cavity (in column 2 and column 5 of table 2) and those inside the DSF (in column 8 of table 2) ranged from -30° to 30° , depended on the wavelengths, and became larger proportionally to the pump power. These differences might be caused by externally induced birefringences inside the fiber, such as twist-induced birefringence, or signal-induced birefringence. Twist induced birefringence is wavelength dependent but not suitable because its dependency is not so severe as this case. [5] Thus, signal induced birefringences in fibers could be added.

When the laser generated at a single polarization mode with the linear polarizer and the laser polarization mode were nearly fixed at the main axes of the fiber under the linear birefringence inside the fiber cavity, [5] the refractive index changes at the fiber main axes could be induced. [9] From the referenced report [9], the maximum phase retardation caused by the signal induced refractive index changes for the 1mW laser signals inside the Er doped fiber with 3.2 m length was

TABLE 2. Measured parameters of birefringence inside the ring fiber cavity with a linear polarizer. * from measured data with polarization analyzer.

Wave-length(nm)	Parameters (degree) With 44mW pump			Parameters (degree) With 100mW pump			Phase retardation through DSF *
	δ	A	B	δ	A	B	
1526.9	210	110	-0.5	200	110	-0.5	220
1528.8	450	350	0.5	420	350	1.0	496
1529.2	440	20	1.0	440	0	2.0	440
1530.0	410	70	-0.5	430	80	-1.0	396
1530.8	400	80	-0.5	430	90	-0.5	370
1531.8	770	70	0.5	790	70	0.5	752
1532.5	710	180	0.0	730	180	0.0	700
1534.2	910	10	0.0	930	10	0.0	884
1535.4	440	90	-1.0	450	90	-1.0	432
1538.2	920	110	-1.0	930	110	-1.0	890
1540.2	520	190	-2.0	520	170	2.0	520

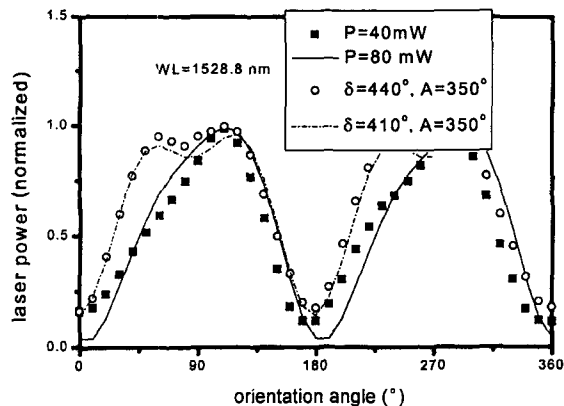


FIG. 13. Fiber laser powers and theoretical gains with linear polarizer as functions of the quarter-wave plate orientation angle at 40 mW pump power and 1528.8 nm. Filled square curve and solid line curve are for the laser with 40mW. Asteric dotted curve and dashed line curve are for theoretical gains with 80mW.

about $\pm 80^\circ$, with directions dependent on wavelength. In the case of 100 mW pump power, the pattern of gain at 1528.8 nm changed, as shown in a solid line curve (2) of Fig.13. The phase retardation caused by the signal induced birefringence at 1528.8 nm was about -30° , as shown in table 2. Zeroing near 1529.2 nm, the induced phase retardation was negatively added to the intrinsic birefringences at shorter wavelengths, and positively added at longer wavelengths. Near 1529.2 nm, only the off axis angle, A , changed with about 20° , i.e., the circular birefringence was induced. Because the induced circular birefringence with 20° was much smaller than the intrinsic linear birefringence with 440° , the phase retardation ($\sqrt{\alpha^2 + \beta^2}l \approx \beta l$) seemed unchanged. Similar features occurred at 1540 nm.

IV. SUMMARY

Using the polarization dependence of ring fiber laser power, the parameters (δ , A , B) of wavelength dependent birefringence inside the ring fiber cavity were measured indirectly.

When a linear polarizer was inserted in the ring type fiber cavity, the patterns of the laser output power

were found to have the complicated function form of birefringence parameters, and these parameters could be clearly obtained with about 5° accuracy. Additionally, the signal induced birefringences with $\pm 30^\circ$ inside Er doped fiber were observed and measured with this method, when the pump power increased.

The measurement methods of the birefringence inside the fiber or the fiber cavity have been continuously developed. Though the methods investigated in this paper were not unique for the characterization of the birefringence, these methods were simple and accurate independent of the polarization state of the measurement equipment. These methods will be useful for the design and evaluation of the fiber and the fiber lasers applied to the high speed light communication system.

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