Measurements of Nonlinear Refractive Index of Optical Fiber by Using Multiple Interference in OFRR

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Abstract

In this paper, a new method for measuring the nonlinear refractive index by using the multiple interference phenomenon occurred in an optical fiber ring resonator (OFRR) is proposed. In OFRRs, input light and circulated light components are added in succession, and then, result in forming a multiple interference output. The OFRR output exhibits nonlinear characteristics between the input and the output power due to the optical Kerr effect, as the input light power increases, as is shown in the bifurcation diagram. In the bifurcation diagram, the output power indicates peaks in the input power range lower than the bifurcation point at which the output changes from stable to periodic state. It is found that the input power at the peak shifts, dependent on the nonlinear refractive index. The nonlinear refractive index can be estimated by applying the measured input power giving the peak point to the numerical relationship between the input power and the nonlinear refractive index. In experiments the nonlinear refractive index of the pure silica core fibers was estimated as $n_2=1.0\times10^{-22}$[m^2/V^2] and $n_2=1.1\times10^{-22}$[m^2/V^2] which are in good agreement with those reported previously.

Keywords

Nonlinear Refractive Index; Optical Fiber Ring Resonator; Bifurcation Diagram; Nonlinear Dynamics

Introduction

In an optical resonator including an optical Kerr medium, Ikeda suggested in 1979 that an output state becomes in its state from stable to periodic, and finally to chaotic as an input light power increases [*Ikeda* et al., 1980]. This originates in an optical Kerr effect that refractive index of a medium changes depending on optical intensity. Since then, much attention has been paid to optical chaos and chaos synchronization generated in optical resonators [*Mirasso*et al., 1996,*Sivaprakasam* et al., 1999, *Suzuki* and*Imai*, 2004]. Some potential applications such as secure communication [*Pecora* and*Carroll*, 1990, *Celka* 1995, *Daisy* and*Fischer*, 1997], temperature and pressure sensing [*Suzuki*et al., 2003] have also been proposed. In this paper, nonlinear dynamics generated in optical fiber ring resonator (OFRR) is applied successfully to measure thenonlinear refractive index of optical fibers.

One of major conventional methods for measuring the nonlinear refractive index of optical fibers uses a cw probe light that composes a Mach-Zehnder interferometer for reading out the phase shift and optical pump pulses that cause cross phase modulation in probe light [*Monerie* and*Durteste*, 1987]. However, this method suffers from high pump power and large reading error in measuring interference fringe shift. Another methods for measuring the fiber nonlinear refractive index are based on XPM or SPM by using high power laser pulses [*Wada* et al., 1992, *Namihira* et al., 1994]. These methods have also disadvantages such as unstable pulses involving worse measurement errors.

In our previous paper, a new method for measuring nonlinear refractive index of fiber by using spectral ratio in nonlinear dynamics generated in modulated OFRR [*Mimuro* et al., 2006] was proposed. In the periodic output state, we found that the spectral ratio between the fundamental frequency component and the harmonic component takes a clear peak and indicates a maximum with increasing nonlinear refractive index. Hence, the nonlinear refractive index of an optical fiber can be measured using the pump power giving the peak of the spectral ratio. The proposed method uses only a cw pump light and takes an advantage of high accuracy.

OFRR output is regarded as a result of multiple interference among the input light and a lot of circulated components in resonator. The circulated light components changes in phase due to the optical Kerr effect occurred in optical fiber in OFRR resonator. In this paper, we pay our attention to the bifurcation diagram in the input-output nonlinear characteristics generated in OFRR with thecw pump light. The input-output characteristics show that the oscillated behavior and a clear peak in OFRR output as the input power increases before the output exhibits the periodic state. We found that the input power giving the peak output depends on the nonlinear refractive index of the fiber. We propose and demonstrate a new method for measuring the nonlinear refractive index with comparable low input power based on the input-output characteristics in OFRR.

Optical Fiber Ring Resonator

An optical fiber ring resonator (OFRR) is made up of an optical fiber and an optical fiber coupler, and the schematic diagram is shown in Fig. 1. In the optical fiber ring resonator, the optical fiber coupler couples the input light component and the light component that circulates a ring, and part of coupled light component propagates in the ring around again, and the other light component is outputted. Therefore, an output optical field $E_{out}(t)$ can be expressed with

$$E_{out}(t) = iE_0\sqrt{\kappa(1-\rho)}e^{i\phi(t)} + (1-\kappa)(1-\rho)E_0 \times \sum_n \left\{i\sqrt{\kappa(1-\rho)}\right\}^{n-1} e^{-\frac{n\alpha L}{2}} \times e^{-i\{n\varphi_0+\sum_{l=1}^{n}\Delta\varphi(t-l\tau)\}}e^{i\varphi(t-n\tau)} \quad (1)$$

where the input light is defined as$E_{in}(t)= E_0\exp\{i(\omega t-\phi(t)\}$ andE_0 and $\phi(t)$ are the amplitude and the random phase term in the input light, κ and ρ are the coupling coefficient and the loss coefficient of the fiber coupler,i is imaginary units,α and L are the loss coefficient of optical power in the optical fiber and the optical fiber length in the resonator, $\tau(=n_0L/c)$ is the circulation time in the resonator, $\phi_0(=kLn_0)$ and $\Delta\phi(=kn_2\int_0^L|E_t(t)|^2)$ are the linear phase shift and the nonlinear phase shift in the resonator, k is the wavenumber of the input light in vacuum, $n_0$and $n_2$are the refractive index and the nonlinear refractive index coefficient in the fiber core. Then, the OFRR output power is derived as follows:

$$P_{out}(t) = \left\langle |E_{out}(t)|^2 \right\rangle, \quad (2)$$

where<> represents the time averaging process.In the above equation, the temporal coherence factor,

$$\gamma(\tau) = \langle\exp\{i[\phi(t)-\phi(t-\tau)]\}\rangle = \exp(-2\pi\Delta\nu\tau), \quad (3)$$

in which Δνstands for the spectral width of light. The above temporal coherence factor is derived by substituting eq.(1) into eq.(2), and is assumed to take unity in numerical analysis in accordance with the use of highly coherent laser light in experiments.

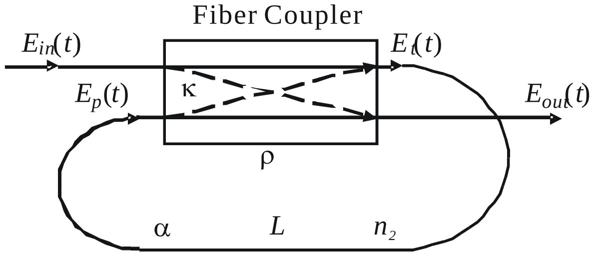

FIG. 1 SCHEMATIC DIAGRAM OF OPTICAL FIBER RING RESONATOR

In eq. (2), the output power of OFRR depends clearly on the nonlinear refractive index of the optical fiber as well as the other fiber parameters. In order to investigate the input-output characteristics, eq.(2) is numerically analyzed under the experimental conditions. Then the input-output characteristics are verified experimentally and the nonlinear refractive index of the optical fiber is estimated.

Input-Output Characteristics in OFRR

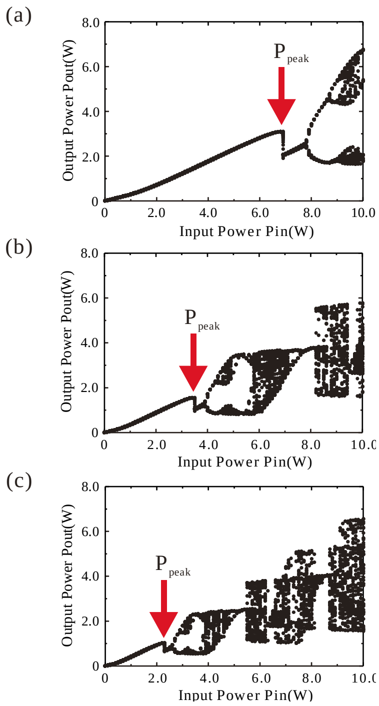

FIG. 2 TYPICAL INPUT-OUTPUT CHARACTERISTICS BY USING BIFURCATION DIAGRAM FOR L=100 [M] IN WHICH N_2=0.5×10^{-22}[M^2/V^2] IN (a), 1.0×10^{-22}[M^2/V^2] IN (b), AND 1.5×10^{-22} [M^2/V^2] IN (c), RESPECTIVELY

The output power of OFRR is analyzed numerically by using the OFRR parameters such as =0.3, =0.1,=0.4 [dB/km], n_0=1.47, n_2=0.5×10^{-22}, 1.0×10^{-22}, 1.5×10^{-22} [m^2/V^2] in accordance with the experimental conditions. The input light is assumed to consist of two wavelengths, =488[nm] and 514.5[nm] on the assumption that an Ar^+

laser is used as the pumping light source in experiments. The numerical results of typical input-output characteristics are shown in Figs. 2-4 in which the length of the fiber resonator is set at L=100[m] in Fig. 2, L=300[m] in Fig. 3, and L=500[m]in Fig. 4, and the nonlinear refractive index is n_2=0.5×10^{-22}[m^2/V^2]in (a), 1.0×10^{-22}[m^2/V^2]in (b), and 1.5×10^{-22} [m^2/V^2] in (c), respectively.

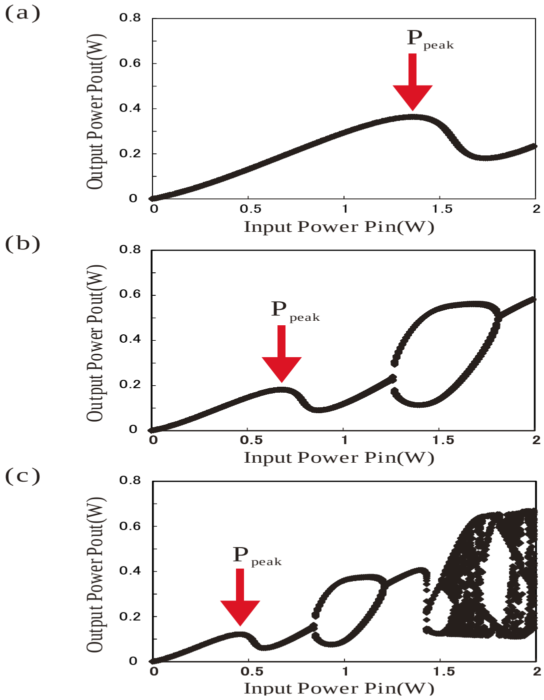

FIG. 3 TYPICAL INPUT-OUTPUT CHARACTERISTICS BY USING BIFURCATION DIAGRAM FOR L=300 [M] IN WHICH N_2=0.5×10^{-22}[M^2/V^2] IN (a), 1.0×10^{-22}[M^2/V^2] IN (b), AND 1.5×10^{-22} [M^2/V^2] IN (c), RESPECTIVELY

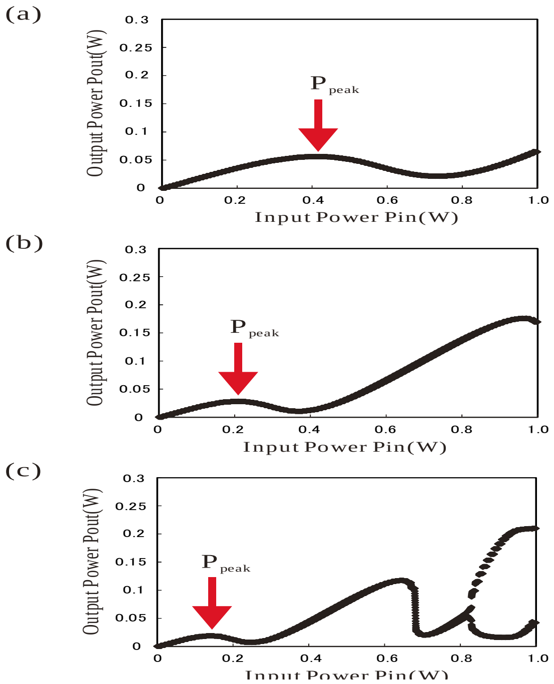

FIG. 4 TYPICAL INPUT-OUTPUT CHARACTERISTICS BY USING BIFURCATION DIAGRAM FOR L=500[M] IN WHICH N_2=0.5×10^{-22}[M^2/V^2] IN (a), 1.0×10^{-22}[M^2/V^2] IN (b), AND 1.5×10^{-22} [M^2/V^2] IN (c), RESPECTIVELY

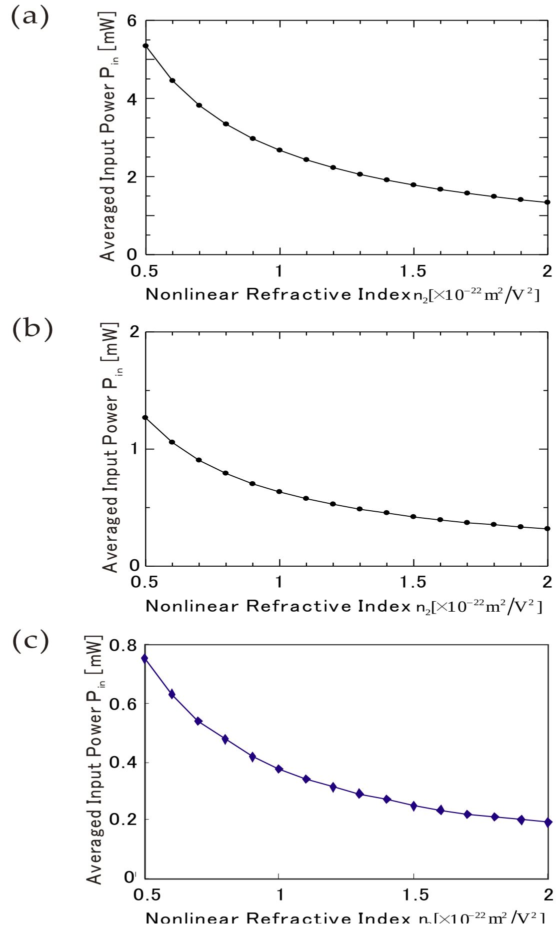

FIG. 5 DEPENDENCE OF AVERAGED INPUT POWER AT PEAK ON NONLINEARREFRACTIVE INDEX COEFFICIENT IN THE CASE OF L=100[M] IN (a), L=300[M] IN (b), AND L=500[M] IN (c), RESPECTIVELY

In these diagrams, the output power increase in an oscillated manner, and reaches the bifurcation point at which the output changes from stable to the periodic state, as the input optical power increases. The bifurcation point moves to the small input power region, as the nonlinear refractive index increases. For example in Fig. 2, the input power at the bifurcation point shifts from 7.9[W] to 2.7[W] by changing in n_2 from 0.5×10^{-22}[m^2/V^2] to 1.5×10^{-22}[m^2/V^2]. The bifurcation point also shift to the lower input power region, as the resonator length becomes longer at each the nonlinear the refractive index level. In the stable region up to bifurcation point, the output power is not linear to the input power and peaks are observed in each graph. The input power giving the peaksdecreases with an increment in the nonlinear refractive index coefficient. For example in Fig. 2, the input power at the peak, P_{peak}, changes from P_{in}=6.9[W] at n_2=0.5×10^{-22}[m^2/V^2] to P_{in} =2.3[W] at n_2=1.5×10^{-22}[m^2/V^2] with L=100[m]. Here, it should be noted that both the input powers at the peaks in the input-output characteristics change in about 30% in the input power, dependent on the phase term ϕ_0 with a period of 2π. The phase term ϕ_0 fluctuates sensitively to the environmental parameters, such as temperature and pressure. From a practical view point, input-output characteristics averaged within one period (2π) in ϕ_0 are reasonable. The averaged dependence of the input power at the peak on the nonlinear refractive index coefficient is shown in Fig.5 in which the dependence of the first peak (peak at smaller input power) is plottedin the case of L=100[m] in (a), 300[m] in (b), and 500[m] in (c), respectively.In each graph, the input power at the peakis inversely proportional to the nonlinear refractive index coefficient, i.e. P_{peak}=760[mW] at n_2=0.5×10^{-22}[m^2/V^2] to P_{in} =250[mW] at n_2=1.5×10^{-22}[m^2/V^2] with L=500[m].

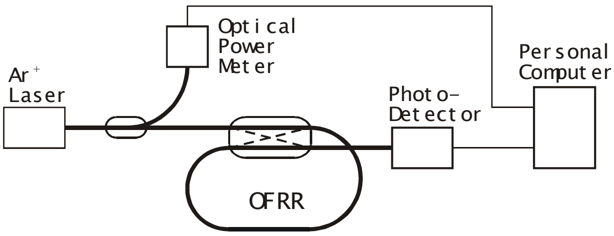

FIG. 6 EXPERIMENTAL SET-UP FOR MEASURING INPUT-OUTPUT CHARACTERISTICS IN OFRR

The input-output characteristics mentioned above are verified in experiments and the nonlinear refractive index is estimated by using the experimental set-up shown in Fig. 6. The pumping light from Ar$^+$ laser (λ=488[nm] and 514.5[nm]) is launched into the OFRR. The input optical power is checked at the optical powermeter in front of the OFRR. The OFRR output is detected by the photodetector and is processed by a personal computer with the input optical power. The OFRR consists of an opticalfiber coupler and an optical fiber with 0.5[μm] cut-off wavelength, 500[m] resonator length, and a pure silica core. Two kinds of optical fiber with a pure silica core were used for the resonator fiber in OFRR. Cut-off wavelength and core diameter for fiber 1 and fiber 2 are λ_{cutoff}=0.55[μm] andλ_{cutoff}=1.2[μm], and d=4.1 [μm] and d=9.3[μm], respectively. The other OFRR conditions arethe same as those used in the numerical analysis.The experimental results of the averaged input-ouputcharacterisitics are shown in Fig. 6. During the measurement, the phase is varied compulsorily so that the averaged chracteristics are obtained. The input optical power is ristricted below 580[mW] due to the practical performanceof the pump laser used.The first peak is clearly observed at around 519.8[mW] input power in (a) and 475.5[mW] in (b).By applying thecritical input power to the input-output relationship given numerically by Fig. 4(a),the nonlinear refractive index coefficient can be estimated to be n_2=0.97×10^{-22}[m^2/V^2] for fiber 1 and n_2=1.06×10^{-22}[m^2/V^2] for fiber 2, which are in good agreement with the previously obtained n_2 value for the pure silica optical fiber[9-11]. The estimation procedure of the present method is illustrated in Fig. 7.

In practice, the input-output characteristics fluctuate in every measurement due to the phase fluctuation in the transmission in OFRR. The fluctuation of the peak power in the input-output characteristics was 8% which leads to the measurement error in the present method.

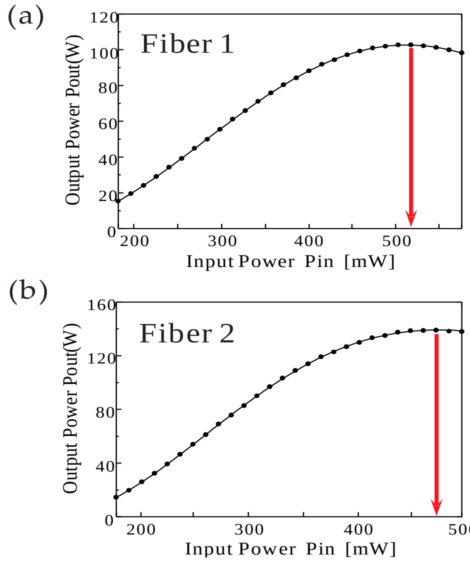

FIG. 7 EXPERIMENTAL RESULTS OF INPUT-OUTPUT CHARACTERISTICS OF OFRR WITH L=500[M] FOR FIBER 1 IN (A) AND FIBER 2 IN (b)

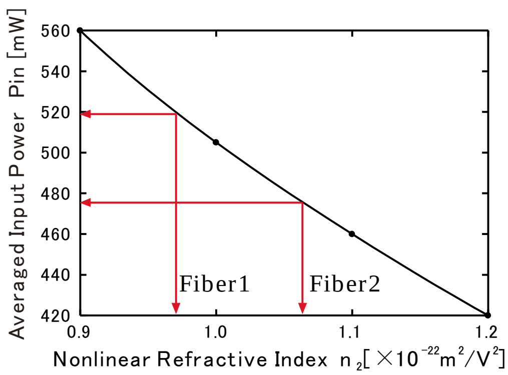

FIG. 8 ESTIMATION OF NONLINEAR REFRACTIVEINDEX COEFFICIENT BY USING INPUT-OUTPUT CHARACTERISTICS OF OFRR

Conclusions

The output optical power of the optical fiber ring resonator increases in a oscillate manner as the input optical power increases. In the bifurcation diagram, the OFRR output exhibits certain peaks until it reaches the bifurcation point. We found that the input powers at these peaks are inversely proportional to the nonlinear refractive index coefficient of the optical fiber. Based on this property in the input-output characteristics in OFRR, the nonlinear refractive index coefficient was estimated as n_2=0.97×10^{-22}[m^2/V^2] and n_2=1.06×10^{-22}[m^2/V^2] for pure silica core optical fibers by measuring the input power at the peak in OFRR output. The present method needs comparable low input optical power with cw laser light, which is greatly advantageous from a practical point of view, while the comparable high peak power is needed in the other methods such as the cross phase modulation. The present method using the input-output characteristics of OFRR can be applied to measuring the other fiber parameters such as linear refractive index and fiber core area as well as to sensing environmental parameters such as temperature and pressure.

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Yoh Imai was born in Iwamizawa, Hokkaido, Japan, on June 22, 1954. He received his B.S., M.S., and Dr. Eng. Degrees from Hokkaido University, Sapporo, Japan, in 1977, 1979, and 1982, respectively, all in applied physics. He was a research associate in the Department of Engineering Science, Hokkaido University from 1982 to 1989. From 1987 to 1989 he was a visiting scholar at the University of Toronto, Canada. He was an Associate Professor in the Department of Computer Science and Electronics, Kyushu Institute of Technology, Japan, from 1989 to 2002. In 2002 he was promoted to a professor in the Department of Electrical and Electronic Engineering, Ibaraki University, Japan. His current interests are the terahertz wave technology and its applications on terahertz sensing and the optical nonlinearity in optical fiber and its applications on optical sensing. He is a member of the Optical Society of America (OSA), the Optical Society of Japan, and the Japan Society of Applied Physics.

Hirohisa Yokota was born in Aichi, Japan, on September 22, 1967. He received the B.E., M.E., and Ph.D. degrees in communication engineering, from Osaka University, Osaka, Japan, in 1990, 1992, and 1995, respectively. In 1995, he joined the College of Engineering, Ibaraki University, Ibaraki, Japan, and now is an Associate Professor. He has been engaged in research on waveguide-type nonlinear optical devices, optical fibers, and optical fiber devices. Dr. Yokota is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), the

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Satoshi Yamauchi was born in Miyagi Prefecture, Japan, on 6 June 1962. He received the B.E., M.E., and Ph.D. degrees in 1986, 1988, and 1991, respectively, all in Electronic Engineering, Tohoku University, Japan. From 1991 he joined OKI Electric Industry Co. Ltd. He was promoted to a Lecturer, Department of Systems Engineering, Ibaraki University in 1997 and now is an Associate Professor, Department of Biomolecular Functional Engineering, Ibaraki University. His current interests are electronic materials and electronic devices. He is a member of the Institute of Electrical and Electronics Engineers (IEEE) and the Japan Society of Applied Physics.