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Proposal for nonlinear refractive index measurement using spectral ratio in modulated OFRR dynamics

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Abstract

A novel method for measuring the nonlinear refractive index of an optical fiber using a spectral ratio between the modulation frequency and a harmonic component in a modulated optical fiber ring resonator (OFRR) is proposed. The spectral ratio between the modulation frequency and the 2nd-harmonics generated by phase-modulation through the OFRR is increased with increasing the input light power and has peaks above 5 W input power, however, the peaks was shifted to the lower input power below 1 W by averaging taken into account of the phase distribution. A experimental setup consisted of an OFRR system and an Ar-laser as a pump light source was used to determine the nonlinear refractive index of an optical fiber. In the experimental results, the peaks of the spectral ratio as a function of the input power was found out at 0.8 W and 0.45 W of the input power corresponding to the input source line at 488.0 nm and 514.5 nm, respectively. The profile was similar to that obtained by the simulation and the nonlinear refractive index of a optical fiber was determined as 1.0×10^{-22} m^2/V^2 by a relationship between the input power giving the peak and the nonlinear refractive index.

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Keywords: Kerr effect; Nonlinear optics; Optical fiber; Optical fiber ring resonator

1. 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 changes to be chaotic with increasing the input light power [1]. This interesting behavior originates in an optical Kerr effect that refractive index of a medium is changed depending on the optical intensity. Since then, a lot of attention has been paid to optical chaos and chaos synchronization generated in optical resonators [2–4], because the optical chaos state has potential to apply to secure communication [5–7], temperature and pressure sensing [8] and so on. In such applications, nonlinear refractive index of optical fiber should be measured precisely to control such optical dynamics. 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 [9]. However, this method suffers from high pump power and large reading error in measuring interference fringe shift.

In this paper, nonlinear dynamics generated in optical fiber ring resonator (OFRR) is applied successfully to measure nonlinear refractive index of an optical fiber. If a phase- or amplitude-modulated light is used as a pump

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light in OFRR, harmonic components for the modulation frequency and a resonant frequency component of OFRR appear in an optical output. Then the output becomes quasi-periodic and chaotic from periodic, as the input power increases. In the periodic output state, we found out in numerical analysis that the spectral ratio between the fundamental frequency component and the harmonic component is dependent on the input light power and takes a clear peak corresponding to nonlinear refractive index of optical fiber in the low power range. Hence, the nonlinear refractive index of an optical fiber can be measured uniquely using the pump power giving the peak of the spectral ratio. The measuring method proposed in this paper has advantages that the refractive index can be measured accurately using only a cw pump light. The proposed method for measuring the nonlinear refractive index of an optical fiber is verified experimentally by using an OFRR setup with Ar-laser.

2. An analytical model of modulated optical fiber ring resonator

An optical fiber ring resonator (OFRR) was set up of an optical fiber and an optical fiber coupler as shown in Fig. 1, where a circulated light is phase- or amplitude-modulated. In this system, the input light component is coupled with the circulated component in the optical fiber coupler and the coupled component propagates in the ring around again, then the coupled light is outputted. In this process, the output optical field E_{out}(t) can be expressed by the following expression:

$$E_{out}(t) = i\sqrt{\kappa(1-\rho)}E_{in}(t) + \sqrt{(1-\kappa)(1-\rho)}E_p(t) \qquad (1)$$

where $E_{in}(t)$ and $E_p(t)$ are the input optical field and circulated optical field in resonator, respectively, κ and ρ are coupling and loss coefficient of the fiber coupler, respectively, and i is imaginary unit. The input light component to the fiber ring is given by

$$E_t(t) = i\sqrt{(1-\kappa)(1-\rho)}E_{in}(t) + \sqrt{\kappa(1-\rho)}E_p(t) \qquad (2)$$

When the input light is cw quasi-monochromatic, the pump optical field can be expressed as

$$E_{in}(t) = E_o \exp[-i(2\pi f)t] \qquad (3)$$

where E_o and f are an optical field amplitude and a frequency of the pump input light, respectively. Therefore, the output light field from the fiber ring is given by

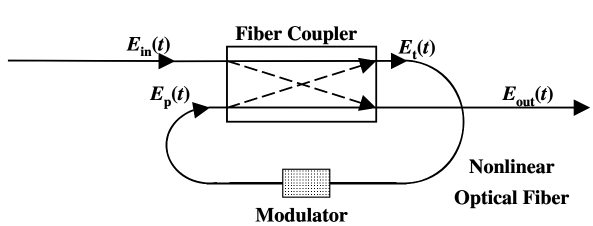

Fig. 1. Schematic diagram of an optical fiber ring resonator.

$$E_p(t) = E_t(t-\tau)\exp\left(-\frac{aL}{2}\right)\exp[-i(\phi_o) + \Delta\phi(t-\tau)] \qquad (4)$$

where α and L are a loss coefficient of optical power and a length in the optical fiber, respectively, τ is a delay time through the resonator, ϕ_o and $\Delta\phi$ are a linear and a nonlinear phase shift in the resonator, respectively. The parameters in the above expression of τ, and ϕ_o are $\Delta\phi$ denoted as

$$\tau = \frac{n_o L}{c}, \quad \phi_o = \kappa L n_o, \quad \Delta\phi = \kappa L n_2 |E_t(t)|^2 \qquad (4')$$

where k is a wavenumber of the input light in vacuum, n_o and n_2 are a core refractive index and a nonlinear refractive index coefficient of the optical fiber, respectively.

When the circulated light is phase-modulated, the output light field from the fiber ring expressed in (4) is rewritten as,

$$E_p(t) = E_t(t-\tau)\exp\left(-\frac{aL}{2}\right)\exp[-i\{\phi_o + \Delta\phi(t-\tau) + m\cos(2\pi f_m t)\}] \qquad (5)$$

where m and f_m are a modulation index and a modulation frequency, respectively. If the circulated light is amplitude-modulated, then (4) is revised as,

$$E_p(t) = E_t(t-\tau)\exp\left(-\frac{aL}{2}\right)\exp[-i\{\phi_o + \Delta\phi(t-\tau)\}] \times \{1 + a\cos(2\pi f_m t)\} \qquad (6)$$

where a ($0 \leqslant a \leqslant 1$) is a modulation depth. And the OFRR output power defined as

$$P_{out}(t) = \langle |E_{out}(t)|^2 \rangle \qquad (7)$$

where $\langle \cdots \rangle$ represents the time averaging process. In case the lights are fluctuated, the phase disturbance should be also reflected on the averaging process in (7).

This paper is concentrated to the phase-modulation process and discussed with the experimental results using an OFRR setup.

3. Experimental setup

Fig. 2 shows schematic diagram of an experimental setup to measure the nonlinear refractive index of an optical fiber by phase-modulation in the OFRR. In this system, an optical fiber ring and a phase modulator were used and they are consisted of 0.6 μm single-mode fiber with 28.6 μm^2 effective cross-sectional area and of PZT driven by a function generator, respectively. A cw Ar-laser with the power spectrum as shown in Fig. 3 was used as pump light source and the output light through the system was characterized by a spectrum analyzer. Details of the parameter values required to analyze the nonlinear refractive index were experimentally determined by using the Ar-laser as follows: