Experimental study of nonlinear switching characteristics of conventional 2×2 fused tapered couplers

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The nonlinear switching characteristics of fused fiber directional couplers were studied experimentally. By using femtosecond laser pulses with pulse width of 100 fs and wavelength of about 1550 nm from a system of Ti:sapphire laser and optical parametric amplifier (OPA), the nonlinear switching properties of a null coupler and a 100% coupler were measured. The experimental results were coincident with the simulations based on nonlinear propagation equations in fiber by using super-mode theory. Nonlinear loss in fiber was also measured to get the injected power at the coupler. After deducting the nonlinear loss and input efficiency, the nonlinear switching critical peak powers for a 100% and a null fused couplers were calculated to be 9410 and 9440 W, respectively. The nonlinear loss parameter P_{N} in an expression of $\alpha_{\mathrm{NL}} = \alpha P/P_{\mathrm{N}}$ was obtained to be $P_{\mathrm{N}} = 0.23$ W.

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The fiber directional coupler is one of the most useful devices used in fiber optical communications and fiber sensors. In conventional applications, the intensity of the optical signal propagating in the coupler is so low that it can be regarded as a linear device, and its properties and mechanisms are understood very clear. As rapid development of the fiber technologies, its applications are spreading wider both in scope and in variations. Fibers and fiber devices are now used in high intensity laser technology field. The total power of wavelength division multiplexing (WDM) systems is also increasing greatly. Nonlinear optical properties of the fiber devices are becoming a hot topic in researches[1]. In fiber directional couplers the index increases due to self-phase modulation and other effects change the coupling coefficient and phase-matching conditions, which will greatly change the coupling ratio of the coupler. The nonlinear optical effects are also attractive in developing new fiber devices, such as high speed all-optical switches[2], logic gates[3], pulse compressors and discriminators[4,5].

There has been quite much work on nonlinear effects in fibers and fiber couplers[6,7]. The basic features of nonlinear switching characteristics in fiber couplers have been described in Ref. [8]. In practical applications there are still many theoretical and technological issues to be studied. To understand detailed mechanisms of the nonlinear effects in fiber couplers, it is necessary to investigate the effect experimentally. In this paper, nonlinear switching characteristics of couplers with different specs in linear range were measured by using 100-fs high intensity laser beams at 1550 nm range. The nonlinear loss in fiber sections was measured and analyzed, and a characteristic power density for the nonlinear transform was estimated. Experimental results were coincident with the theoretical analyses and simulations obtained by using super mode equations.

Key elements of the experimental setup are indicated schematically in Fig. 1. The source consisted of a titanium-doped sapphire mode-locked laser and an optical parametric amplifier (OPA), providing pulses with 100-fs pulse-width and 1-kHz repetition rate. Its integrated spectrum was measured as shown in Fig. 2, in which a fitted Gaussian curve was also shown as $U(\lambda) = U_0 \exp[-(\lambda - \lambda_{\mathrm{p}})^2/(\Delta\lambda)^2]$ with peak wavelength of 1541 nm and 1/e maximum half line-width of 38 nm. The fitting was perfect except for the low power pedestal parts, which meant that the laser pulse could be expected with a good Gaussian waveform. From Fourier-transform-limit relation, the pulse-width could be estimated as $\tau \geq 0.4413/\Delta f \approx 56$ fs, which was in good agreement with the measured results by auto-correlation for Ti:sapphire 800-nm pulse of ~ 100 fs. Then the duty-cycle of the laser pulses was estimated to be about 10^{-10}.

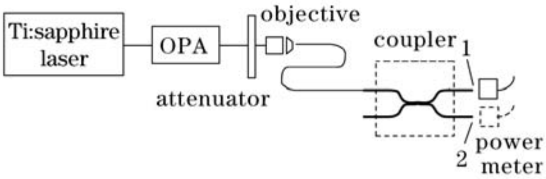

Fig. 1. Experimental setup.

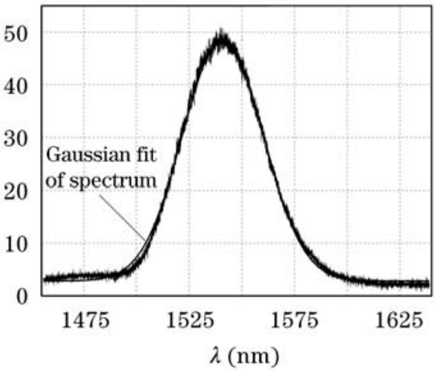

Fig. 2. The measured spectrum of the laser beam.

The attenuator plate after laser was used to adjust the intensity of injecting power. The laser beam was focused into the fiber with a 5× microscope objective, and the transmitted light was detected by a power meter. The input and output fiber bundles of the coupler were 0.5 m long.

Making use of the experimental setup, we measured the power distribution variation in two output branches versus input intensity of 100% and null couplers, as shown in Figs. 3(a) and (b). The vertical axis of Fig. 3 is the ratio of one port output to the sum of two port outputs; the horizontal axis is the input power, measured by a conventional optical power meter after the microscope objective. It was clear that the coupler showed intensity-dependent switching characteristic. In low power range, the input power went out totally from port 1 (i.e. the same fiber before fusing) for 100% coupler, and from port 2 for null coupler. With the increasing of input power, there were more and more output power obtained from the opposite port, and at the critical point the output from the two ports got equal. The measured critical average power was 35 mW for 100% coupler, and 37 mW for null coupler. Taking the duty cycle into account, the peak powers were 3.5×10^8 and 3.7×10^8 W, respectively.

To get the nonlinear parameters inside couplers, it is necessary to compare the experiment results with the simulation based on the equations describing the nonlinear switching effects[8]. We investigated the effects in detail by using super-mode theory, which will be reported in another paper. Figure 4 shows the calculated switching characteristics by using super-mode theory and finite-difference methods. From these curves, it is clear that, to null couplers, under the condition with low input power, the power would output from port 1; as input power increasing, more and more power is transferred to port 2 for nonlinear effects; when keeping on raising the input power, the power outputting from port 2 would reduce, and all power would output from port 1 ultimately. As to 100% coupler, raising the input power would lead most of the power to output from port 1, instead of port 2 as in low power inputting condition. In a word, nonlinear effects induced by high input power change the symmetry structure of coupler to an asymmetry one, and alter the transmission properties of couplers, so all power input the coupler will output from the direct connected arm.

It can be seen that the experimental curves were in good agreement in the range below the critical power P_c qualitatively. The range higher than the critical power was not yet reached under the present experimental condition. Further work is being undertaken.

To calculate the exact value of critical power P_c from the measured data, we must get the input and output power just at the edge of the coupling region. There are two factors, nonlinear loss and coupling efficiency at the input and output fiber ports, which will bring about great influence to the determination of the real power inside the fiber at the coupling range of the devices. In Ref. [6] the nonlinear loss was checked experimentally and the related coefficients were obtained by using a phenomenological model. The fiber loss including the nonlinear loss can be considered as a linear function of the input power, and can be expressed as $\alpha = \alpha_L + \alpha_{NL} = \alpha_L(1 + P/P_N)$, where P_N is a characteristic parameter for the nonlinear loss, and α_L is the linear loss. Propagation equation can then be solved to give an expression for the power variation with the distance:

$$P(z) = P_0 \frac{P_N \exp(-\alpha_L z)}{P_N + P_0[1 - \exp(-\alpha_L z)]}, \quad (1)$$

where $P_0 = P(0)$ is the input power inside the fiber. Namely, the coupling efficiencies were not taken into

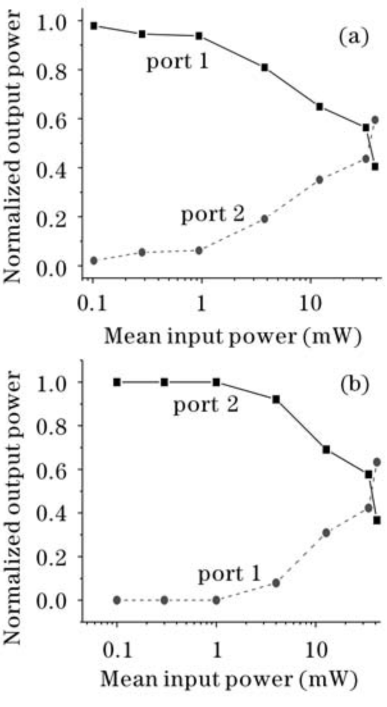

Fig. 3. The normalized output power of a 100% coupler (a) and a null coupler (b) versus the mean input power.

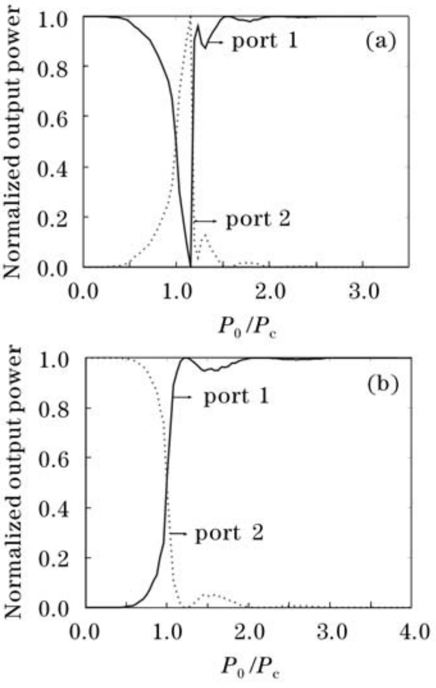

Fig. 4. Calculated nonlinear switching characteristics of a null coupler (a) and a 100% coupler (b).

account. In practical measurements, measured input and output power should be expressed as $P_0 = \eta_1 P_{\mathrm{in}}$ and $P_{\mathrm{out}} = \eta_2 P(l)$, where l is the length of the fiber in measurement. The measured reciprocal transmission can then be expressed as

$$\frac{P_{\mathrm{in}}}{P_{\mathrm{out}}} = \frac{1}{\eta_1 \eta_2}[\exp(\alpha_{\mathrm{L}} l) + \frac{\exp(\alpha_{\mathrm{L}} l) - 1}{P_{\mathrm{N}}}\eta_1 P_{\mathrm{in}}]. \qquad (2)$$

The linear loss can be obtained from the specs of the fiber to be $\alpha_{\mathrm{L}} = 0.2$ dB/km as usual, and the output coupling loss can be neglected to set $\eta_2 = 1$. Then the nonlinear loss parameter P_{N} and input coefficient η_1 can be obtained from the slope and intercept of $(P_{\mathrm{in}}/P_{\mathrm{out}}) \sim P_{\mathrm{in}}$ lines fitted from experimental data.

Figure 5 shows a curve of transmission as a function of input optical power measured in a fiber with length of 1 m. From the slope 201 MW^{-1} and ordinate intercept 2190 of the fitted line, the nonlinear loss parameter and the input coefficient can be evaluated as $P_{\mathrm{N}} = 0.23$ W and $\eta_1 = 4.6 \times 10^{-4}$. The input coupling efficiency was very low, which was because the diameter of output beam from OPA was quite large and a suitable focus lens was not available temporarily.

By using these data and the duty cycle of the ultrashort laser beam, the nonlinear switching thresholds of the couplers, namely the critical power P_{c} in Fig. 4, could be calculated to be about 9410 W for 100% coupler and 9440 W for null coupler, respectively in its peak value. It is shown that the nonlinear effect on loss is much larger than that on index. Mechanisms of nonlinear loss will be discussed elsewhere.

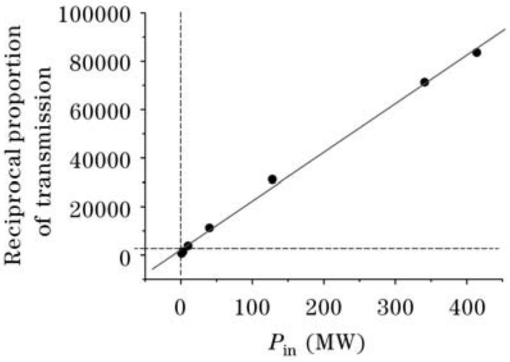

Fig. 5. Total transmission versus incident peak power.

In conclusion, the nonlinear switching characteristics of fused couplers have been experimentally investigated by using a femtosecond pulsed laser beam at C band. Experimental results were in good agreement with numerical simulation qualitatively. The nonlinear loss in the fiber section of the input and output ports of the couplers was also measured and estimated. By deducting the nonlinear loss and the input coupling efficiency, the critical peak power for nonlinear switching in fused fiber couplers was calculated to be about 9410 W for 100% coupler and 9440 W for null coupler, respectively. The nonlinear loss parameter in an expression of $\alpha_{\mathrm{NL}} = \alpha P/P_{\mathrm{N}}$ was obtained to be $P_{\mathrm{N}} = 0.23$ W. The parameters obtained in this work are believed to be useful for developing fiber devices and components in the field of high intensity laser systems.

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