Paper

Reduction of Mode-Coupling and Single-Mode Excitation in Multimode Fibers by Use of Ultra-Short Optical Pulses

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The fundamental mode can be launched in the multimode(MM) fibers with high accuracy by suppressing modal speckle by using broad-bandwidth excitation sources such as ultra-short pluses. As temporal coherence length of broad-bandwidth sources is very short, temporal interference between the modes and thus the presence of speckle is prevented. In this paper, single-mode(SM) excitation of step-index and graded-index multimode fibers with light sources with short temporal coherence lengths is demonstrated using a Ti:Sapphire laser with wavelengths of 790 nm and 836 nm and pulse widths of 60 ~ 90 fs. As a result, the stability of the spatial beam profile was verified by coupling the output of a MM fiber into SM fiber and SM excitation in the presence of mode-coupling for the MM fibers was confirmed by experiment.

Keywords : Ultra-short optical pulse, Broad-bandwidth optical source, Multimode optical fiber, Mode-coupling, Single-mode excitation

1. Introduction

As optical power levels extractable from current single mode(SM) fiber amplifiers are reaching regions where optical nonlinearities cannot be ignored, it is becoming increasingly important to develop methods for reducing these nonlinearities. For an alternative to SM fiber amplifiers, multimode(MM) fibers are one of candidate for high power SM fiber amplifiers in the absence of mode-coupling, which degrades seriously the amplifier performance[1]. MM optical fibers can transmit high energy and can be easily used for connection or splicing since they can reduce optical nonlinear effects because of its large core diameter and effective core area A_{eff}. Therefore, the advantage of using MM fibers is to transmit high power and to reduce nonlinear effect. However, for multimode fibers, one of disadvantages is mode-coupling due to modal interference between different modes and microbending-induced mode-coupling. The MM fibers thus exhibit a speckle pattern at the output of the MM fiber. These phenomenon leads to modal noise[2)-(3] in the area of local area networks(LANs) and interconnections with multimode fibers[4].

The presence of speckle patterns due to modal interference between different modes can be eliminated by use of optical sources with short temporal coherence. As a result, the fundamental mode is launched in these MM fibers when suppressing multimode-dependent speckles provided that a broad-bandwidth optical sources such as ultra-short pulses are used to excite the MM fiber[5)-(6]. Therefore, the single-mode excitation in the MM fibers is possible by employing broad-bandwidth excitation sources such as ultra-short pulses. It is also important to study the characteristics of mode-coupling in MM fibers for application and design of MM fibers.

In this paper, single-mode excitation of step-index and graded-index multimode fibers is demonstrated using a Ti:Sapphire laser with the wavelength of 790 nm and 836 nm and pulse widths of 60 ~ 90 femtosecond(Fs)[7)-(8]. Then the mode-coupling coefficients and launching efficiencies are determined experimentally from diffraction half-angle of the output pattern exiting from MM fibers and compared with theoretical estimates. The stability of spatial beam profile was verified by coupling the output of a MM fiber into SM fiber and the resultant SM excitation in the presence of mode-coupling in the MM fibers.

2. Experimental System and Its Theoretical Background

The construction of optical measurement system is schematically shown in Fig.1. The wavelength variable Ti:Sapphire laser pumped by Ar ion laser was used for optical source with short temporal coherence. The MM optical fiber was fixed in the setup and excited by femtosecond pulses from Ti:Sapphire laser. Then, the speckle pattern appears in the far-field region of the output end. The diffraction half-angle was measured using far-field patterns exiting from the MM fiber. It allows us to estimate mode-coupling coefficient of the MM fiber. The single-mode excitation characteristics such as a coupling efficiency were also estimated for output powers from MM optical fiber coupled into the SM optical fiber.

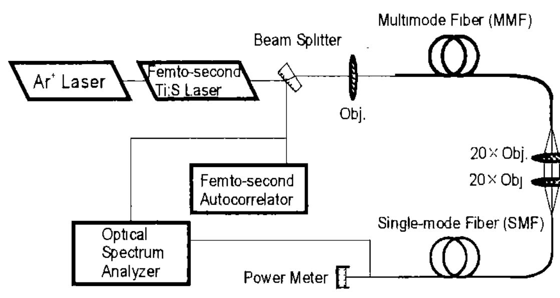

Fig.1 Optical setup for measurement of mode-coupling and launching efficiency into MM fibers.

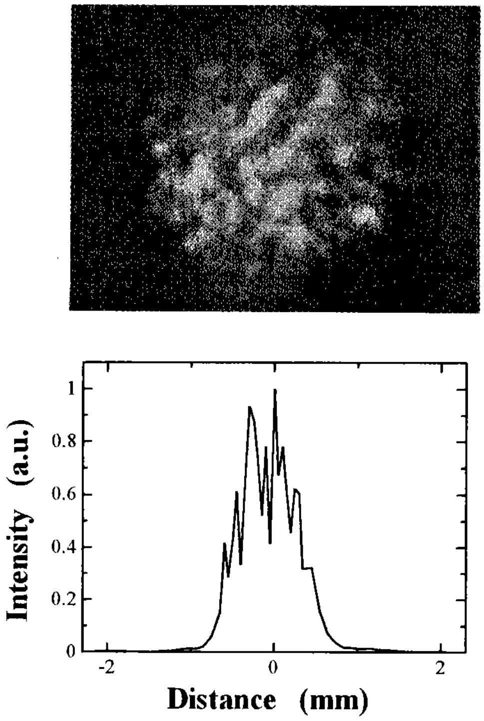

Fig.2 Speckle patterns of laser light emerging from the MM fiber for continuous wave laser which are emitted from a Ti:Sapphire laser of wavelength λ=836nm.

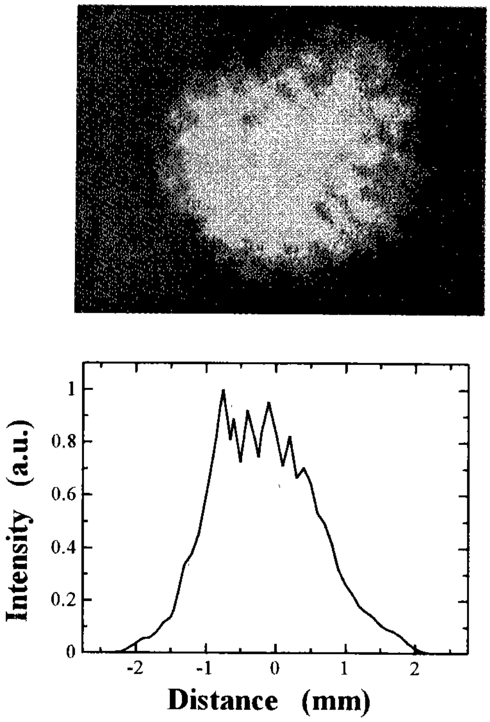

Fig.3 Speckle patterns of laser light emerging from the MM fiber for ultra-short optical pulses which are emitted from a Ti:Sapphire laser of wavelength λ=836nm.

The theoretical background for launching efficiency into SM fiber is as follows. A diffraction-limited optical source is used to couple the fundamental mode into a MM fiber of core diameter d and length z. The output from the MM fiber can then be coupled into the subsequent SM fiber with a launching efficiency[7]

$$\eta \approx \left(\frac{\theta_0}{\theta_m}\right)^2 \qquad (1)$$

where θ_0 and θ_m are the far-field diffraction half-angle of the fundamental mode and the output from the MM fiber, respectively[9]-[10].

Here, the far-field diffraction half-angle of the fundamental mode gives rise to

$$\theta_0 = \frac{\lambda}{2d} \qquad (2)$$

and λ is the excitation wavelength. It can be shown that owing to mode coupling θ_m increases with z as[11]-[12]

$$\theta_m^2 = 4Dz + \theta_0^2 \qquad (3)$$

where D is the mode-coupling coefficient. Therefore, the maximum obtainable launching efficiency into the SM fiber is then given by substituting eq. (2) and (3) into eq. (1) and yields

$$\eta = \left(1 + \frac{16d^2Dz}{\lambda^2}\right)^{-1} \qquad (4)$$

Thus, the actual fiber parameters of a variety of MM fibers including erbium-doped multimode fiber(EDF) are listed in Table 1. From these parameters the launching efficiencies are estimated by taking into account the mechanism of mode-launching. Also, mode-coupling coefficients are determined by measurements of diffraction half-angle from the output of the MM fiber.

3. Measurements and Discussion

3-1. Speckle Pattern As continuous wave (CW) lasers have a long temporal coherence length, different modes propagating in MM fibers can interfere with each other, producing modal interference at the output of the MM fiber. The speckle pattern changes rapidly with various kinds of fiber perturbations or movements and even with small variations of temperature. As a result, the coupling of the speckle pattern into a SM fiber becomes very unstable. Therefore, an accurate measurement of η cannot be made easily, and it is necessary to find a method for measuring coupling efficiency in the presence of speckle patterns. The interference between different modes can be eliminated by use of optical sources with a short temporal coherence length, such as a femtosecond pulse source or a broad-band spectral output from a superfluorescent fiber laser. Here, a typical ultra- short laser (wavelengths 790 ~ 836nm, repetition rate ~ 80 MHz) emitting femtosecond pulses is employed as a light source. Speckle patterns produced in the far-filed region and its intensity scan across the central part of the pattern are shown in Fig.2 and Fig.3 for the CW laser and the pulsed laser of the same wave- length λ=836nm, respectively. It is obvious that the radiation patterns clearly exhibit a speckle in Fig.2 and the speckle pattern is observed to vary in time. On the other hand, in the dimmed speckle of Fig.3 the temporal features of pattern are stable and, as a result, the coupling of output light from MM fiber into a SM fiber remains stable and easy to achieve high efficiency.

3-2. Mode-Coupling and Launching Efficiency Some parameters of MM fibers used in the experiment, the resultant mode-coupling coefficient and launching efficiency are shown together in Table 1. Both of mode-coupling coefficient and launching efficiency are obtained by measuring diffraction half-angles and using eq. (4). The far-field diffraction half-angle of the output from MM fiber is defined as an angle reduced to $1/e^2$ of peak power. The output end of MM fiber is scanned precisely with a rotating micrometer and the output powers are plotted with a fixed photodetector. The wavelength of ultra-short optical pulse is chosen as 790nm and the pulse width is measured to be 89 fs from femtosecond autocorrelator.

In Table 2, some measurements on the mode-coupling coefficient and launching efficiency with λ=790nm and 836nm

Table 1. Specifics and parameters of graded-index(GI) and step-index(SI) MM fibers and erbium-dope multimode fiber(EDF).

Fiber (Sample Number)	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9
Refractive Index Distribution	GI	GI	GI	GI	GI	GI	GI	SI	EDF
Core Diameter (μm)	50	50	50	50	62.5	62.5	62.5	50	18.4
Cladding Diameter (μm)	150	150	125	125	125	125	125	125	125
Numerical Aperture	0.212	0.124	0.212	0.212	0.300	0.300	0.300	0.134	0.069
Manufacturing Process			VAD	VAD	VAD	OVD	MCVD	VAD	
Fiber Length (m)	0.52	4.00	1.80	1.60	1.80	1.50	1.00	2.00	1.50
Diffraction Half-Angle (rad)	0.142	0.107	0.159	0.161	0.195	0.220	0.178	0.118	0.048
Mode-Coupling Coefficient (10^{-3}) D	9.7	0.71	3.5	4.1	5.3	8.1	7.9	1.7	0.31
Launching Efficiency (%) η	0.32	0.53	0.24	0.25	0.11	0.0084	0.13	0.46	20.4

Table 2. Mode-coupling coefficients and launching efficiencies of several fiber samples for λ=790nm and 836nm.

Fiber (Sample Number)	No. 3	No. 8	No.9
λ= 790 (nm)			
Diffraction Half-Angle (rad)	0.159	0.118	0.048
Mode-Coupling Coefficient (10^{-3}) D	3.5	1.7	0.31
Launching Efficiency (%) η	0.24	0.46	20.4
λ= 836 (nm)			
Diffraction Half-Angle (rad)	0.158	0.090	0.049
Mode-Coupling Coefficient (10^{-3}) D	3.5	1.0	0.31
Launching Efficiency (%) η	0.28	0.85	21.9
Experiment [λ= 836 (nm)]			
Launching Efficiency (%) η	0.28	0.64	15.0

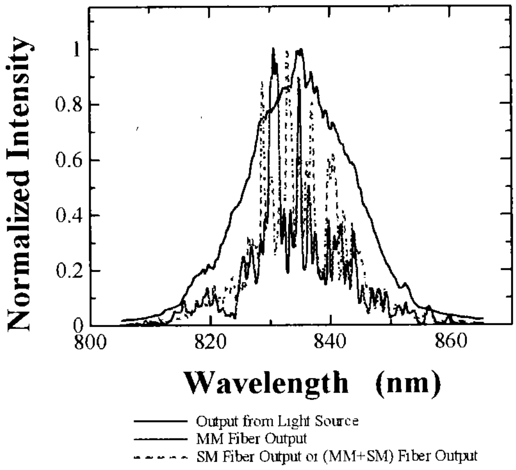

Fig.4 Optical spectra of ultra-short pulse from a Ti:Sapphire laser (solid line) and those after it was propagated in the MM fiber only (chain line) and the SM fiber followed by the MM fiber of Sample No.3 (dashed line).

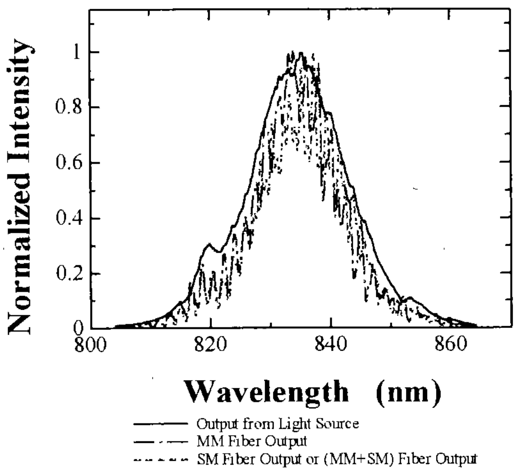

Fig.5 Optical spectra of ultra-short pulse from a Ti:Sapphire laser (solid line) and those after it was propagated in the MM fiber only (chain line) and the SM fiber followed by the MM fiber of Sample No.9 (dashed line).

are shown for the sake of comparison. It is noted that a mode-coupling coefficient and launching efficiency are diverse from one sample to another because of the different parameters and profiles of refractive index as well as the different manufacturing processes. In contrast, a slight increase of launching efficiency η is followed by an increase in operating wavelength λ as seen in Table 2. From Table 2 the launching efficiency is found to increase with increase of wavelength because the number of mode is reduced when the wavelength is large. Also, theoretical launching efficiency η is comparable to experimental one at λ=836nm. It is concluded that both values are coincident with each other to some extend. Thus, we found that the launching efficiency η increases when designing the fibers with small core diameter and small NA whereas mode-coupling decreases as cladding diameter is increased(6). Because the mode-coupling is induced in the fiber with microbending, the microbending can be reduced with an increase of cladding diameter. Also, it is clear from eq. (4) that the stable single-mode excitation without mode coupling is achieved by keeping the mode-coupling coefficient small(8)-(9).

3.3 Single-Mode Excitation The high efficiency of single-mode excitation in MM optical fibers was demonstrated by launching a femtosecond optical pulse on the large core diameter or large NA fibers. To analyze optical spectrum waveforms, a spectrum analyzer is used to test the light before it was coupled into MM fiber and after it was propagated in the SM fiber followed by the MM fiber. The experimental results are shown in Fig.4 and Fig.5, respectively. Here, the SM fiber used for the present experiment is 9.5μm core diameter and 125μm cladding diameter. The normalized frequency is V=3.77 at λ=836nm. The cutoff wavelength of the second-mode in the SM fiber is obtained as 1310nm so that the fiber dose not operate at single-mode regime. However, the fundamental mode is mainly excited by connecting the SM fiber to the preceding MM fiber with fine alignment of optical axis, and the single-mode operation is confirmed by visual inspection with use of a phosphor card. In the measurements of output spectrum, the fiber samples of No.3 and No.9 are employed in the respective figures of 4 and 5. Although the spectrum measured at the output of SM fiber is largely dependent on the coupling conditions, it is noted that the spectrum of light propagated through the MM fiber and coupled into SM fiber exhibits more undulations with respect to the wavelength. Compared the spectrum of sample No.3 with that of fiber sample No.9, the smoothed spectrum distribution is obtained for No.9. Note that the shape of the spectrum is critically dependent on the coupling condition. The spectral measurement in the fiber with large mode-coupling coefficients is sensitive to the phase between the fundamental and the higher-orders modes ; i.e., an energy content of higher-order modes of only 1% in the output of the MM fiber can lead to perturbations of the shape of the spectrum of as much as $\approx$10%(6). This means the fact that a small mode-coupling coefficient can be expected for No.9 sample.

Next, we estimate single-mode excitation length of MM fiber. The length is defined as the distance how long the fundamental mode can propagate down the MM fiber without mode-coupling. The launching efficiency is related to M^2 value that is typically

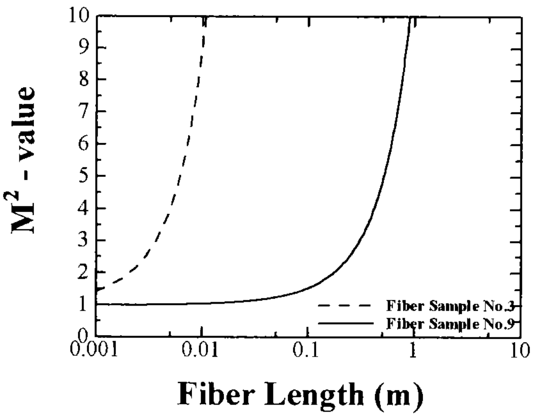

Fig.6 M^2-values at a wavelength of 836nm in fibers sample No.3 and No.9 as a function of fiber length.

used to characterize the quality of near-diffraction-limited optical beams as shown in eq. (5)[7].

$$1/\eta \approx \sqrt{M^2} \tag{5}$$

It is well known that M^2 is the fundamental Gaussian beam counterparts except for the quantity. For $M^2=1$, they reduce to the fundamental Gaussian beam equations. The quantity M^2 is then a numerical expression of beam quality with $M^2=1$ being a perfect Gaussian beam, and higher values of $M^2>1$ indicating "poor" quality. As will be shown, it is this number which expresses how many times larger the diameter of a focused beam is, compared with the focus-diameter for a pure fundamental Gaussian beam[13].

Therefore, under SM excitation of a MM fiber, the amount of power propagating in the fundamental mode decrease as an increase of fiber length due to micro-bending-induced mode-coupling[6]. The M^2-value is shown in Fig.6 as a function of fiber length, as calculated from eq. (5) for fiber samples of No.3 and No.9. The input wavelength is chosen as 836nm. The low-micro-bending fiber of No.9 sample indeed allows to obtain an $M^2<1.2$-value for fiber length up to 4.0cm. Also, $M^2<2.0$-value is maintained for the fiber length up to 17.4cm. Compared the curve of No.3 sample with that of fiber sample of No.9, the single-mode excitation length of No.9 is longer than No.3. Therefore, it turns out that higher launching efficiency results from longer single-mode excitation length.

4. Conclusion

In this paper, it has been shown that single-mode excitation of step-index and graded-index multimode fibers with light sources with a short temporal coherence length is demonstrated using a Ti:Sapphire laser with the wavelength of 790 nm and 836 nm and pulse widths of 60 ~ 90 fs. The mode-coupling coefficients and launching efficiencies are discussed for a variety of MM fibers. Also, it is discussed here how single-mode excitation is dependent on the length of MM fiber.

The single-mode excitation in the presence of mode-coupling can be achieved in MM fibers when mode-coupling and modal noise in MM fiber are eliminated by use of optical sources with short temporal coherence length. The launching efficiency η increases as core diameter and NA are small whereas cladding diameter and wavelength are increased. As a result, it is possible to achieve a highly stable single-mode excitation by increasing launching efficiency and reducing mode-coupling.

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References

(1) M.E.Fermann, A.Galvanauskas, G.Sucha, and D.Harter, Appl. Phys., Vol.B65, pp.259-275 (1997).
(2) E.G.Rawson and J.W.Goodman, Proc. Soc. Photo-Optical Instrum. Eng., Vol.243 in Applications of Speckle Phenomena, pp.28-34 (1980).
(3) R.E.Epworth, Laser Focus, Vol.17, No.7, pp.109-115 (1981).
(4) G.D.Khoe, H.P.A.v.d.Boom, W.Li, H.de Waardt, Y.Koike, and T.Ishiguro, Proc. 2nd Workshop on Fiber and Optical Passive Components (WFOPC 2000), pp.154-163 (2000).
(5) M.E.Fermann, A.Galvanauskas, D.Harter, J.D.Minelly and J.E.Caplen, Tech. Dig. Optical Fiber Communication (OFC'98), pp.39-40 (1998).
(6) M. E. Fermann, Opt. Lett., Vol.23, No.1, pp.52-54 (1998).
(7) Y.Suzuki, S.Sato, and M.Imai, Tech. Rep. IEICE, OFT2000-16, pp.49-54 (2000)
(8) Y.Suzuki, S.Sato, and M.Imai, Proc. 2000 Japan-China Meeting on Optical Fiber Science and Electromagnetic Theory(OFSET2000), pp.349-352 (2000).
(9) D.Gloge, Appl. Opt.,Vol.10, No.10, pp.2252-2258 (1971).
(10) U.Griebner, R.Koch, H.Schonnagel, and R.Grunwald, Opt. Lett., Vol.21, No.4, pp.266-268 (1996).
(11) D.Gloge, Bell Syst. Tech. J., Vol.51, No.8, pp.1767-1783 (1972).
(12) W.A.Gambling, D.N.Payne, and H.Matsumura, Appl. Opt., Vol.14, No.7, pp.1538-1542 (1975).
(13) M.W.Sasnett, D.R.Hall, P.E.Jackson. The Physics and Technology of Laser Resonators, New York: Adam Hilger, pp.132-142, (1989).
(14) L.Marshall, Laser Focus, Vol. 4, pp.26-28 (1971).

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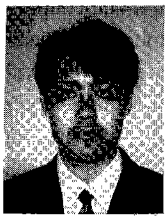

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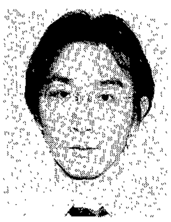

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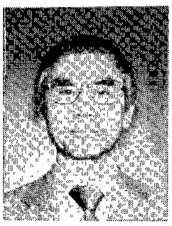

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