A Comparison of Six Techniques for Nonlinear Coefficient Measurements of various Single Mode Optical Fibers

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Abstract A comparison of six techniques for nonlinear coefficient (n2/A*eff*) measurements of various optical fibers using Pulsed-LD SPM, CW-LD SPM, sinusoidally modulated signal-SPM, XPM, self-aligned Interferometric, and FWM methods is first demonstrated. The (n2/A*eff*) obtained from the six different methods were in good interlaboratory agreement except for dispersion compensating fiber (DCF).

Introduction: Accurate determination of the nonlinear coefficient (n2/A*eff*){n2 is the nonlinear refractive index, A*eff* is the effective area} of optical fibers is required for the ultra-long amplified optical transmission systems. To date, the nonlinear coefficient of the optical fibers has been measured by using the self-phase modulation (SPM) method with a pulsed laser diode (LD) (P-SPM)[1], the SPM method with dual CW-LDs (CW-SPM) [2], the cross-phase modulation (XPM) method [3], self-aligned Interferometric (INT) method [4], sinusoidally modulated signal-SPM (S-SPM) method [5], and four wave mixing (FWM) method [6].

Heretofore, ITU-T (n2/A*eff*) round robin measurements for various optical fibers were coordinated by Prof. Y. Namihira of University of the Ryukyus (formerly KDD) have been successfully performed [7-9].

This paper first presents the results of the interlaboratory fiber nonlinear coefficient (n2/A*eff*) measurements for various optical fibers such as standard single mode fiber (SMF), cut-off shifted fiber (CSF), dispersion shifted fiber (DSF), non-zero DSF (NZDSF) and large effective area DSF (LEDSF), and dispersion compensating fiber (DCF) using six different techniques such as the P-SPM [1] , CW-SPM [2], XPM [3], INT[4], S-SPM [5], and FWM [6] methods at 1550nm.

Experiments: The experimental set-up of the (n_2/A_{eff}) measurements for the various single mode optical fibers are shown in Fig.1. In Fig.1, (a), (b), (c), (d) and (e) are P-SPM method, CW-SPM method, XPM method, INT method, S-SPM, and FWM methods, respectively. Here, n_2 can be estimated by (n_2/A_{eff}) multiplying the A_{eff}. The A_{eff} was measured by the far-field scan (FFS) technique [10]. The parameters of six kinds of single mode optical fibers are shown in Table 1. These fibers were circulated to the five Laboratories such as University of the Ryukyus (formerly KDD), Furukawa, University of Geneva, Pirelli Labs., Muroran Institute of Technology.

P-SPM method: In Fig.1(a), as a pulsed-LD, transform limited (TL) Gaussian pulse-LD were used [1]. The output optical pulse due to SPM was measured by the optical spectrum analyzer (OSA). As the input optical power increases, the maximum phase shift increases in proportion to the input peak power. The (n_2/A_{eff}) can be obtained from the numbers of peaks in the SPM broadened spectra [1].

CW-SPM method: In Fig.1(b), the optical beat signal was derived from dual CW-LDs operating at around 1550nm [2]. The beat signal was then amplified in a preamplifier (EDFA1) and transmitted through a optical band pass filter to suppress the amplified stimulated emission and a polarizer to a following high power erbium amplifier (EDFA2).

XPM method: In Fig.1(c), the probe signal power is set relatively weak so that (n_2/A_{eff}) in FUT is dominantly caused by amplified strong pump CW-LD through XPM and that the effect of SPM is negligible. When pump CW-LD or CW-SLD is modulated in its intensity, probe CW-LD is modulated in this phase through XPM [3].

INT method: In Fig.1(d), the Interferometric method is based on the detection of the Kerr phase shift by a self-aligned interferometer. Here, the distributed feedback laser (DFB), Erbium doped fiber amplifier (EDFA), polarization controller (PC), Farady mirror (FM), and fiber Bragg grating (FBG) were used [4].

S-SPM method: In Fig.1 (e), the S-SPM method is based on SPM effect estimation. This technique consists simply in propagating an optical signal sinusoidally modulated by means of an electro-optical $LiNbO_3$ modulator. The γ -factor estimation is achieved using a simulation tool capable of reproducing the evolution of signal spectra along the fiber and doing a comparison between acquired experimental data and simulation result [5].

FWM method: In Fig.1(f), pump (DFB-LD1) and probe (DFB-LD2) sources are tunable with a temperature and current controller. The LD1 of pump source was amplified with a EDFA to compensate an insertion loss of polarization optics, and passed through a tunable band-pass filter (BPF) with =1nm to eliminate the ASE noise of EDFA. The /2 wave plate was used to rotate the input azimuth of linearly polarized light of LD1. In contrast, the output light of LD2 was depolarized with a depolarizer to examine the depolarization effect on FWM efficiency. Otherwise, the depolarizer was deleted in the setup so that the FWM efficiency was measured in linearly polarized states of LD1 and LD2 [6].

Results and discussions: The results of interlaboratory (n2/A*eff*) and n2 measurements at random polarization states (RP) using six different techniques of P-SPM, CW-SPM, XPM, INT, S-SPM, and FWM for a SMF, a CSF, two kinds of DSFs, two kinds of NZDSFs, a LEDSF and a DCF at 1550nm are summarized in Tables 2 and 3, respectively.

In Tables 2 and 3, n2(RP) = η n2(LP), η =1.0 for P-SPM, η =8/9 for CW-SPM, S-SPM, and FWM, and the polarization factor η =2/3 for XPM were used. Here, LP represents the linear polarization state.

Here, concerning the results of the self-aligned Interferometric (INT) method [4], the (n2/A*eff*) values were larger than that of the other methods. Then, a correction (scaling) factor of ~0.8 with respect to the mean values of the other methods were used. Such a scaling could easily arise from an erroneous estimation of the absolute peak power used for this measurements (underestimate of the power by a factor of just 0.8). Therefore, the special correction factor of k =0.8 {(*) in Tables 2 , 3, Figs.1,2} were used for the INT method because of the experimental error.

Meanwhile, in FWM method at Muroran Institute of Technology, only one (n2/A*eff*) measurement of 20 km long DSF was measured at present, however, they will be measured (n2/A*eff*) of another fiber samples in the near future.

Fig. 2 show estimated values of n2 at random polarization states for various optical fibers as a function of six different measurement methods. Fig. 3 indicates the estimated values of n2 at random polarization states for six different measurement methods as a function of various optical fibers.

From Tables 2 and 3, it was found that the average values of n_2 at RP of SMF, CSF, DSF, NZDSF, LEDSF, and DCF were ~2.62, 2.43, 4.80, 4.16. 3.19 and 12.1 x 10^{-10} [1/W], respectively. Also, the average values of n_2 at RP for SMF, CSF, DSF, NZDSF, LEDSF and DCF were ~2.21, 2.14, 2.25, 2.31, 2.32, and 2.78 x 10^{-20} [m^2/W], respectively.

The average n_2 values of ~2.25 x 10^{-20} [m^2/W] of DSFs at random polarization states are in good agreement with that of 2.1 - 2.3 x 10^{-20} [m^2/W] range of published results, respectively.

Conclusions: From the interlaboratory nonlinear coefficient (n2/A*eff*) measurements for various optical fibers, the (n2/A*eff*) obtained from the six different techniques such as pulsed-LD SPM method, CW-SPM method, a XPM method, a self-aligned Interferometric (INT) method, a sinusoidally modulated signal SPM method, and FWM method were found to be a good agreement with each methods except for DCF.

It was confirmed that the average values n2 at random polarization state obtained from these different methods were 2. ~2.3 x 10^{-20} [m^2/W] for SMF, CSF, DSF, NZDSF and LEDSF except for DCF of ~2.8 x 10^{-20} [m^2/W], respectively.

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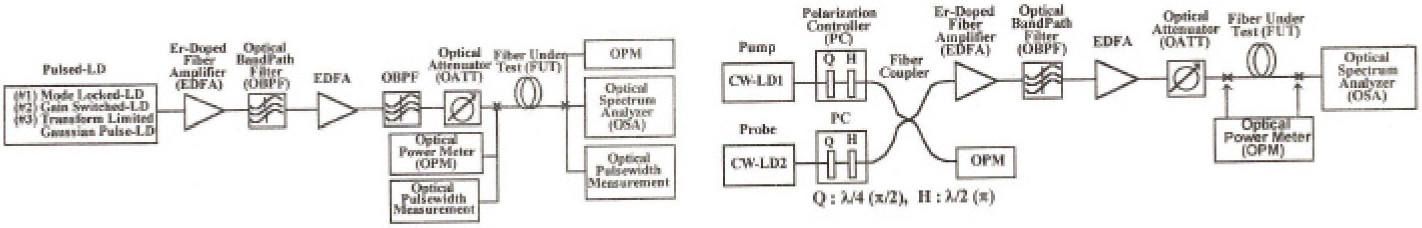
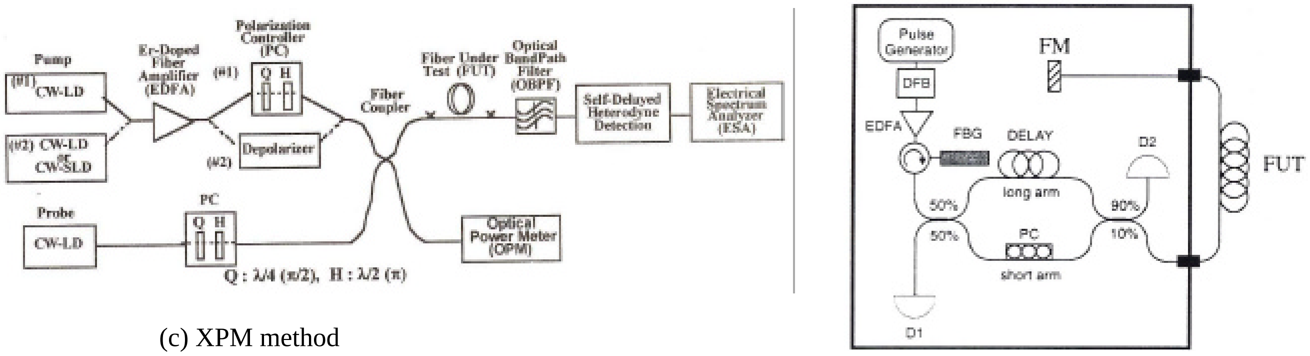
Table 1 Fiber parameters for various single mode optical fibers.

Fibers	SMF	CSF	DSF	NZDSF	LEDSF	DCF
D@1550nm [ps/(nm -km)]	16.3	19.4	-0.58	-2.19	-2.48	-109.1
Aeff@1550nm [ƒ m̂ ’ 9]	84.6	88.2	46.8	55.6	72.8	22.9



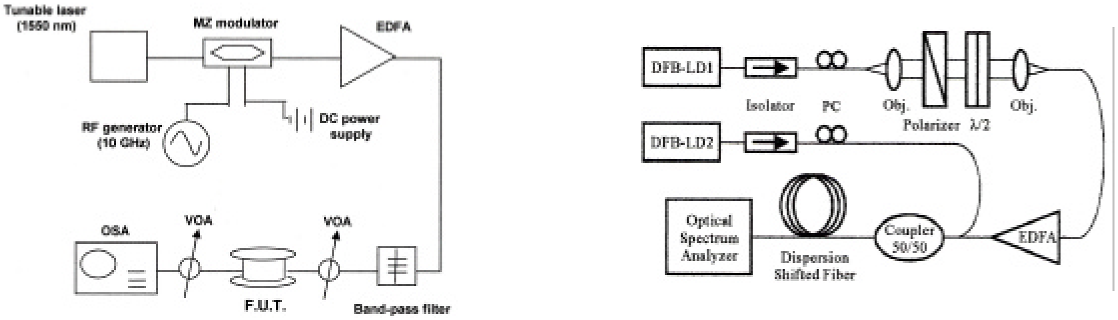
(a) Pulsed-LD SPM (P-SPM)

(b) CW-LD SPM (CW-SPM)



(c) XPM method

(d) Self-aligned Interferometric



(e) Sinusoidally modulated signal SPM (S-SPM)

(f) Four wave mixing (FWM)

Fig.1 Experimental set up for six different (n2/Aeff) measurement methods.
(a) Pulsed LD SPM(P-SPM), (b) CW-LD SPM (CW-SPM), (c) XPM
(d) Self-aligned Interferometric (INT), (e) Sinusoidally modulated signal SPM (S-SPM),
(f) Four wave mixing (FWM)

Table 2 Measured values of (n2/Aeff) at random polarization states for various optical fibers using six different methods.

Fibers	(n2/Aeff) • ×10^{-10} [1/W]							
	P-SPM	CW-SPM	XPM	INT (*)	S-SPM	FWM	Ave	ƒ Ð
SMF	2.62	2.60	2.45	2.53	2.90	-	2.62	0.172
CSF	2.45	2.31	2.14	2.58	2.65	-	2.43	0.206
DSF	4.76	5.09	4.69	4.51	5.05	4.70	4.80	0.227
NZDSF	3.94	4.26	3.70	4.18	4.75	-	4.16	0.395
LEDSF	3.01	3.25	3.00	3.18	3.51	-	3.19	0.209
DCF	11.86	11.56	13.00	14.02	10.12	-	12.11	1.481

(*) :Using a correction factor of 0.8. (-) :Not Measured

Table 3 Estimated values of n2 at random polarization states for various optical fibers using six different methods.

Fibers	n2 • ×10^{-20} [m^2/W]							
	P-SPM	CW-SPM	XPM	INT (*)	S-SPM	FWM	Ave	ƒ Ð
SMF	2.22	2.20	2.07	2.14	2.45	-	2.21	0.145
CSF	2.16	2.04	1.89	2.27	2.34	-	2.14	0.182
DSF	2.23	2.39	2.19	2.11	2.36	2.22	2.25	0.105
NZDSF	2.20	2.37	2.05	2.33	2.63	-	2.31	0.216
LEDSF	2.19	2.37	2.18	2.31	2.56	-	2.32	0.155
DCF	2.72	2.66	2.97	3.21	2.33	-	2.78	0.331

(*) :Using a correction factor of 0.8. (-) :Not Measured

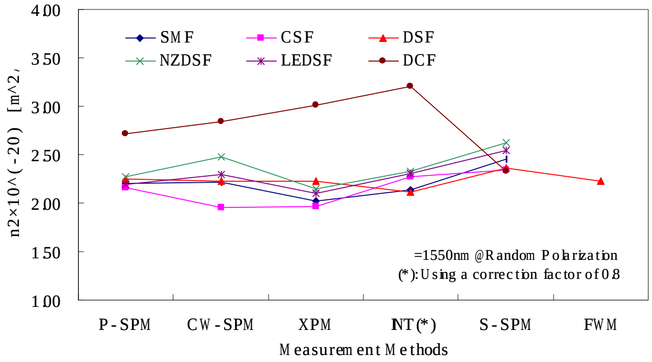


Fig.2 Estimated values of n2 at random polarization states for various optical fibers as a function of six different measurement methods.

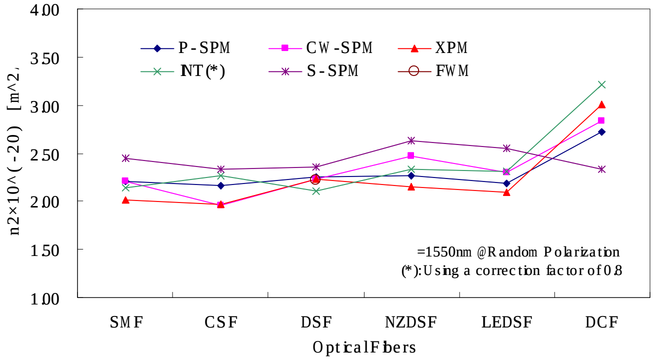


Fig.3 Estimated values of n2 at random polarization states for six different measurement methods as a function of various single mode optical fibers.