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Reliable determination of optical fiber nonlinearity using dispersion simulations and improved power measurements

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***Abstract*—We have improved the accuracy of continuous-wave self-phase modulation method for measuring nonlinearity of optical fibers. The evaluation of measurement uncertainty shows that the most significant source of uncertainty is the measurement of fiber-optic power. However, chromatic dispersion can also have significant effect on the apparent results, if it is not taken properly into account. We demonstrate means to achieve an expanded uncertainty of 2 % (coverage factor $k = 2$) for the measurement of nonlinear coefficient n_2/A_{eff}. Also the metrological aspects related to the determination of the nonlinear coefficient and measurement uncertainty are discussed.**

***Index Terms*—Optical fiber dispersion, Optical fiber measurements, Optical Kerr effect, Photodetectors.**

I. INTRODUCTION

THE nonlinear refractive index, n_2, is one of the key parameters, which define the data transmission rate limits for modern optical telecommunication systems in terms of used optical power and spacing of wavelength channels in wavelength division multiplexed systems [1], [2]. The interest for studying nonlinear properties of optical fibers has now also been extended to various types of single mode fibers [3]-[7], where dispersion and nonlinear properties can differ significantly from one type to another.

As the severity of the nonlinear effects is dependent on the intensity distribution inside the fiber, it is convenient to use nonlinear coefficient n_2/A_{eff} to represent the magnitude of this phenomenon. For the time being, the methods to standardize the nonlinearity measurements of optical fibers are under study [8]. The direct continuous-wave self-phase modulation (CW SPM) method is the most applied one of these measurements. Also the need of careful uncertainty analysis in the determination of n_2/A_{eff} is evident, as for instance the deviations in the final report of the ITU-T intercomparison were in the order of several percents [6]. Even the four laboratories, all using the CW SPM method did not succeed to have a remarkably better agreement between each other. The recent development of the various techniques has not brought the results of participating laboratories any closer to each other, as the agreement levels of earlier comparisons [8]-[15] have not improved significantly. The common problem for these comparisons is that the measurement uncertainties of the participating laboratories are not evaluated.

In this paper, we present improvements on the CW SPM method in order to increase its accuracy and repeatability. The major source for uncertainty is typically the determination of optical power launched into the fiber under test. For this purpose we have built and characterized a Spectralon®-coated integrating sphere detector for high fiber-optic power [16]. Secondly, in order to take the effects of dispersion into account, we have combined measurements of the CW SPM method with numerical simulations [17]. This brings improvements by a factor of three in the uncertainty of determination of n_2/A_{eff} [5], [7]. As a final outcome, we demonstrate a measurement setup for n_2/A_{eff} with the expanded uncertainty of 2 % ($k = 2$) and discuss the issues related to accurate determination of fiber nonlinearity.

II. OPERATIONAL PRINCIPLE OF CW SPM METHOD

In our measurements, we utilize the CW SPM method as outlined in Fig. 1. Two continuous wave external cavity diode lasers are operated around 1550 nm with the wavelength spacing of 0.3 nm. The laser beams are set to have same linear polarization using polarization controllers and a polarizer after the beams are combined. The signal is then amplified and launched into the fiber under test (FUT). The optical power is measured at the end of the tested fiber using the 99 % branch of the coupler. The total attenuation of the coupler, splice connection, and the tested fiber are taken into account by carefully characterizing their attenuation, as well as the reflection from the fiber end.

When high optical power at the two laser wavelengths is launched into the fiber under test, sidebands lying symmetrically around fundamental wavelengths are generated due to the self-phase modulation. The nonlinear phase shift φ_{SPM} of the signal can be obtained from the measurement of the intensity ratio I_0/I_1 of the fundamental wavelength to the first-order sideband [4], [5]

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$$\frac{I_0}{I_1} = \frac{J_0^2\left(\varphi_{\mathrm{SPM}}/2\right)+J_1^2\left(\varphi_{\mathrm{SPM}}/2\right)}{J_1^2\left(\varphi_{\mathrm{SPM}}/2\right)+J_2^2\left(\varphi_{\mathrm{SPM}}/2\right)} . \qquad (1)$$

In Eq. (1), J_n is the Bessel function of n^{th} order. The nonlinear coefficient n_2/A_{eff} can then be found from the relation [4], [5]

$$\frac{n_2}{A_{\mathrm{eff}}} = \frac{\lambda_0[\mathrm{m}]}{4\pi L_{\mathrm{eff}}[\mathrm{m}]}\left(\frac{\varphi_{\mathrm{SPM}}[\mathrm{rad}]}{P_{\mathrm{AVG}}[\mathrm{W}]}\right) , \qquad (2)$$

where λ_0 is center wavelength in vacuum, L_{eff} is effective fiber length, and P_{AVG} is average optical power. Above analysis does not take into account that the apparent values for n_2/A_{eff} depend on measurement conditions in the presence of fiber dispersion. It neglects the effects of dispersion by assuming that the nonlinear coefficient can be solved directly from the slope of the nonlinear phase shift as a function of optical power [4], [7]. In order to take the dispersion into account, simulations based on Nonlinear Schrödinger Equation (NLSE) [2] are combined with measurements. This approach is well suitable for various measurement conditions and fiber types in order to attain high measurement accuracy.

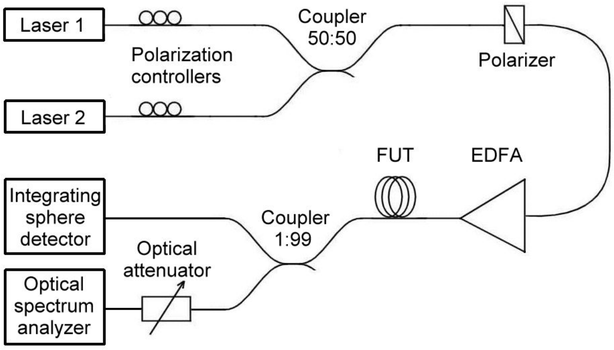

Fig. 1. Measurement setup of continuous-wave self-phase modulation method.

III. POWER MEASUREMENTS

The measurement of optical power launched into the fiber under test is the major source of uncertainty in determination of fiber nonlinearity. In Eq. (2), P_{AVG} is the most demanding quantity, affecting directly the value of n_2/A_{eff}, to be accurately determined. With many commercial power meters it is possible to reach uncertainty levels of only a few percents at the best. For instance in our previous measurement setup the total expanded uncertainty ($k = 2$) of 6.4 % was dominated by the uncertainty of 5.4 % in power measurement [7]. Therefore, it is important to pay special attention to the design or selection of the optical power meter in order to reach satisfactory uncertainty levels.

The improvement in optical power measurement is achieved by using a precision fiber optic detector, built and characterized in our laboratory [16]. The detector consists of a Spectralon®-coated integrating sphere (diam. 50.8 mm), equipped with a fiber adapter and an InGaAs photodiode. The power responsivity of the sphere detector is traceable to the cryogenic radiometer. The angular and spatial variations in power responsivity, as well the aging of the sphere in high power use, have been found negligible. In order to extend scale realization of high fiber optic power up to 650 mW, the linearity of the power responsivity of the sphere detector was studied using the AC/DC-method [18]. The AC/DC method determines the derivative of the response v. power curve at each DC power level using a small-amplitude sinusoidal AC modulation.

Test measurements with different aperture diameters in front of the InGaAs photodiode revealed that the nonlinear power responsivity of the integrating sphere detector, presented in Fig. 2, is almost completely originating from the properties of the InGaAs photodiode. Although the nonlinearity could be reduced by using a smaller aperture in front of the InGaAs photodiode [19], it was decided to apply the correction of Fig. 2 instead, since a smaller detector aperture would reduce the signal levels.

The expanded uncertainty ($k = 2$) in high fiber-optic power measurements is 0.93 % at the power levels below 100 mW [16], [20] and for the higher power levels, up to 650 mW, it is 1.3 %. As the power measurement is performed after passage through the fiber under test, the attenuations of the fiber connection, coupler, and studied fiber have to be taken into account. This adds an additional uncertainty component in the determination of fiber optic power, which is highly dependent on the repeatability of the optical connectors. With splices the repeatability can be, depending of the fiber type, in order of ~0.01 dB (0.23 %) compared to e.g. FC/PC optical connectors with repeatability ~0.3 dB (7.1%). Therefore splices are used for all connections between the power meter and the forward end of the fiber under test to minimize the uncertainty originating from the determination of the attenuation between the optical power meter and the fiber front end.

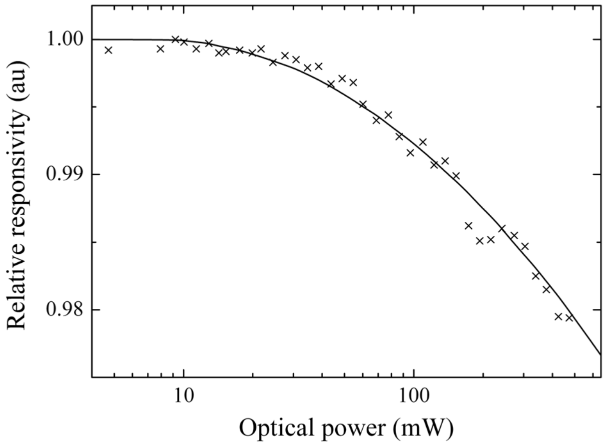

Fig. 2. Nonlinearity of spectral power responsivity of the integrating sphere detector at 1550 nm wavelength. Crosses indicate measured nonlinearities at each power level and the 2^{nd} order polynomial curve is fitted to the measurement data.

IV. SIMULATIONS OF FIBER DISPERSION

A. Simulations of Light Propagation in Optical Fiber

Originally the CW SPM method neglects the effects of dispersion [4]. It has been concluded that this can cause a measurement error of several percents depending on the measurement conditions [5], [7]. To overcome this problem, we have combined measurement results with numerical simulations. In this modeling of light propagation in the fiber, we use the Nonlinear Schrödinger Equation (NLSE) [2], [21] to calculate the nonlinear phase-shift experienced by the fundamental dual-frequency signal. Our implementation [17] in Matlab® is based on the split-step Fourier method [2] allowing flexible adjustment of various measurement parameters, such as chromatic dispersion, attenuation, fiber length, wavelength difference, and launched optical power. Finally, the best-fit solution for n_2/A_{eff} is found using the least-squares method in the comparison of simulated and measured phase shift curves.

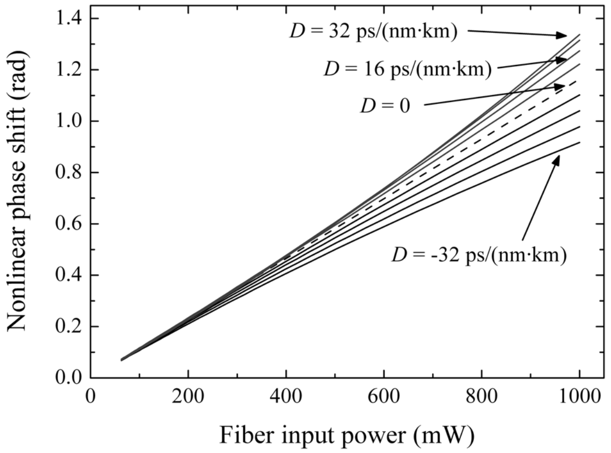

Fig. 3. Simulated effects of dispersion on nonlinear phase shift. The dashed straight line represents the condition, where the fiber dispersion is set to zero. In all simulations fiber length was set to 500 m, wavelength difference to 0.3 nm and $n_2/A_{\mathrm{eff}} = 2.9 \cdot 10^{-10}\ \mathrm{W}^{-1}$. Only the dispersion parameter is either increasing or decreasing with steps of 8 ps/(nm·km) from simulation to another.

The magnitude of dispersion effects on the results of nonlinearity measurement depends on the other measurement parameters. Therefore it is impossible to generate a straightforward correction factor even for well-known fiber types. For instance the simulated effect of fiber dispersion on nonlinear phase shift curves is presented in Fig. 3. The dashed straight line represents the condition, where the fiber dispersion is set to zero. This condition is also equal to the assumption that the equations of conventional CW SPM method are based on. The simulated phase shift curves lying around the zero-dispersion curve are differing from the adjacent simulations only by value of the dispersion parameter by steps of 8 ps/(nm·km). In all simulations, the fiber length was set to 500 m, wavelength difference to 0.3 nm and $n_2/A_{\mathrm{eff}} = 2.9 \cdot 10^{-10}\ \mathrm{W}^{-1}$. If the curve with $D = 16$ ps/(nm·km) is further inspected, we can clearly see that fiber parameters corresponding to standard single-mode fibers (SMFs) can already differ significantly compared to the case where dispersion is neglected. Also in different measurement conditions the effect of fiber dispersion on nonlinear phase shift curves will be different. However, by comparing measured nonlinear phase shift values with simulated ones, calculated with NLSE, reasonably better agreement can be achieved as compared to the conventional CW SPM method which neglects the effects of fiber dispersion.

B. Combination of Simulations and Measurements

In the CW SPM method, phase shift is measured as a function of fiber input power. In the conventional approach of CW SPM method, nonlinear phase shift curves are expected to be straight lines and therefore the apparent value of n_2/A_{eff} should not depend on applied optical power. However, in the presence of fiber dispersion the measurement conditions will affect apparent results of n_2/A_{eff} causing significant deviation between the apparent and true values. This effect can be taken into account by determining the fiber dispersion and using appropriate dispersion model in simulations for the fiber under test.

With SMFs having anomalous dispersion, phase shift curves bend upwards [7]. This is the case in Fig. 4, where the measured phase shift curve at different power levels is bending upwards.

The solid black curve in Fig. 4, representing the best fit for the measurement results, is plotted with the measurement results (crosses) by using the values $n_2/A_{\mathrm{eff}} = 2.9 \cdot 10^{-10}\ \mathrm{W}^{-1}$ for the nonlinear coefficient and $D = 16$ ps/(nm·km) for the dispersion parameter. If the dispersion is neglected and only Eq. (1) and Eq. (2) are used, the fitting of measurement results will lead to an error of a few percents in n_2/A_{eff}. For comparison, the dashed dark grey curve is simulated with the same value of $n_2/A_{\mathrm{eff}} = 2.9 \cdot 10^{-10}\ \mathrm{W}^{-1}$, but with $D = 0$. This clearly shows that without taking dispersion into account, we end up overestimating the values of n_2/A_{eff} with fibers having anomalous dispersion. Opposite effect will occur in the case of normal dispersion.

For example, if the effects of dispersion would be neglected in the results presented in Fig. 4, the value of n_2/A_{eff} is overestimated by 2.3 %. Also, clearly better agreement by 60 % between measured and calculated phase shift curves can be achieved in the least-square sense, if the measurement results are combined with simulations utilizing NLSE instead of calculations neglecting effects of dispersion.

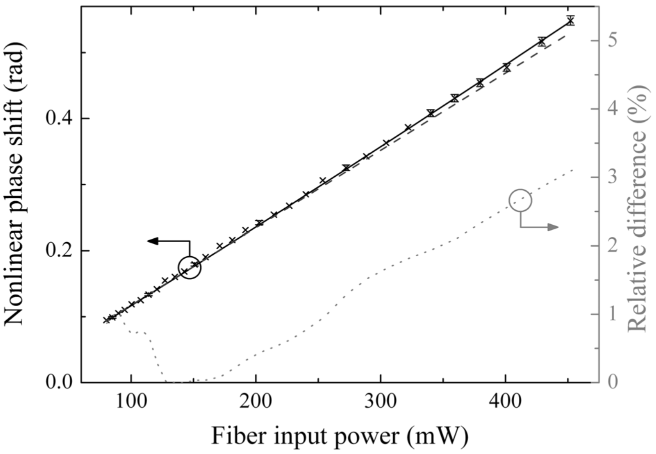

Fig. 4. Fit to the nonlinearity data of 500 m long single-mode fiber when dispersion (D = 16 ps/(nm·km)) is taken into account (solid black line). If the dispersion is neglected in simulations, the result of fitting is significantly worse, as presented by the dashed dark grey curve. Dotted grey curve, using the right-hand side scale, represents the relative difference between the two simulated phase shifts with and without dispersion.

V. MEASUREMENT RESULTS AND UNCERTAINTY ANALYSIS

A. Uncertainty Analysis

The reliability of the uncertainty analysis [22] is based on the traceability of the individual quantities and estimations of the relative errors of the measurement instruments. For instance, in the case of optical power, the traceability chain limits the minimum uncertainty of transfer and working standards. If uncalibrated instruments are used, significant systematic errors can occur in determination of fiber nonlinearity as the nonlinear phase shift is directly proportional to the value of optical power (Eq. 2). The fiber optic power can be measured directly from the output end of the fiber with expanded uncertainty ($k = 2$) of 0.93 % up to 100 mW [16], [20] and 1.3 % up to 650 mW. The uncertainty component due to determination of the attenuation of the splice and coupler, between the optical power meter and front end of the fiber under test, is 0.7 %. This results in the total power measurement uncertainty component of 1.5 % in Table 1.

TABLE 1. UNCERTAINTY BUDGET (95 % LEVEL OF CONFIDENCE) FOR THE CW SPM METHOD WITH RELIABLE MEASUREMENTS OF HIGH FIBER OPTIC POWER AND APPROPRIATE CORRECTION FOR THE EFFECTS OF DISPERSION.

Uncertainty component	Uncertainty (%)
Power measurement P_{AVG}	1.5
Simulated effects of fiber dispersion	0.5
Optical spectrum analyzer $I_0/I_1 \rightarrow \varphi_{SPM}$	1.2
Wavelength uncertainty λ_0	0.1
Fiber length L	0.4
Expanded uncertainty ($k = 2$)	2.0

The value of n_2/A_{eff} is determined by comparing the measured and simulated phase shifts using the least-squares method. The main advantage of this technique is that effects of dispersion can be taken into account, and because of this, a systematic error of couple of percents can be avoided. Determination of the fiber dispersion, dispersion slope, and the fitting itself are thus estimated to induce an uncertainty component of only 0.5 %. The accuracy in the determination of fiber dispersion is not directly transferred to the uncertainty in n_2/A_{eff}, but depends also on other measurement parameters. Simulations utilizing NLSE provide a tool to take effects of dispersion into account. Otherwise, with especially long fibers or high optical power the errors can be remarkable. If special fibers with greatly different dispersion properties are studied, uncertainty contributions as low as 0.5 % might be difficult to achieve.

Also other sources of uncertainty need consideration while the measurement results are analyzed. The relative measurement capability of the optical spectrum analyzer (OSA) can become critical. If the linearity of the spectral power responsivity of the OSA is not considered, it can also cause systematic errors that may easily become significant. This is important especially in the measurements where the nonlinear sideband signal I_1 is weak compared to the fundamental signal I_0 and practically the whole dynamic range of the OSA is used. As an outcome, the uncertainty component of 1.2 % is introduced by measurement of the intensity ratio.

A reasonable accuracy in the determination of the used wavelength and fiber length can be obtained with various means. For the determination of wavelength, we use a wavelength meter that is traceable to molecular transitions of rubidium and iodine. The corresponding uncertainty in Table 1 is 0.1%. For the fiber length, mechanical measurement has been found to be most convenient. If the method would be used for deployed fibers another way to determine fiber length is needed. This has to be taken into account while the uncertainty budget is evaluated. For mechanical length measurements, the corresponding uncertainty of 0.4 % is included in the determination of n_2/A_{eff}.

The total expanded uncertainty in Table 1 has been improved from 6.4 % ($k = 2$) of Ref. [7] to 2.0 % by replacing the commercial power meter with a more reliable detector and utilizing NLSE simulations of fiber dispersion with the measurement results.

B. Measurements for SMFs with different fiber parameters

We performed test measurements for two single-mode fibers (ITU-T G.652) having different dopants in the core and cladding. With these modifications in the composition of fibers, their nonlinear properties were slightly altered. Between repetitive measurements, the measurement setup was completely dismounted and fibers were re-spliced to the measurement setup.

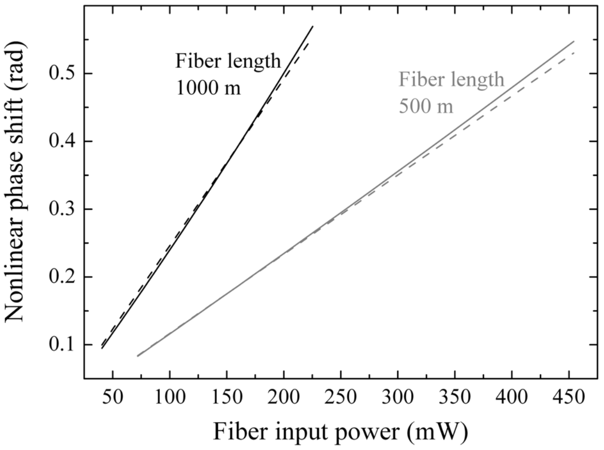

Fig. 5. Simulated phase shift curves for fiber lengths of 500 m and 1000 m having $n_2/A_{\mathrm{eff}} = 2.9 \cdot 10^{-10}\ \mathrm{W}^{-1}$. Solid curves are simulated with dispersion parameter D = 16 ps/(nm·km) and for the dashed curves $D = 0$.

When the dispersion is taken into account, the results of the measurements are found to be insensitive to the measurement conditions, such as the fiber length and wavelength spacing. The data in Table 2 show that, if the dispersion is not taken into account, the apparent results for n_2/A_{eff} depend on sample lengths and we will have systematic errors over 2 % in the determination of the nonlinear coefficient. Both fibers have a dispersion parameter of 16 ps/(nm·km) and a dispersion slope of 0.08 ps/(nm^2·km). Due to the dispersion, values for nonlinear phase shift φ_{SPM} and nonlinear coefficient n_2/A_{eff} vary depending on the measurement parameters. Only for ~1000 m long SMFs the apparent results of two techniques intersect [7]. This is also visible in Fig. 5, where especially the result for the 500 m long SMF is affected, as the linear fit differs significantly from the case when dispersion is present. The accuracy of simulation based on NLSE in the determination of n_2/A_{eff} is relatively insensitive to the error in the determination of fiber dispersion. For instance, even 5 % error in the determination of fiber dispersion affects less than 0.1 % the apparent value of n_2/A_{eff} with SMFs.

VI. CONCLUSIONS

At the moment the determination of nonlinear coefficient n_2/A_{eff} of optical fibers is mainly limited due to the optical power measurement and fiber dispersion. The issues related to the power measurement traceability and uncertainty analysis need careful consideration, when better agreement between different laboratories and measurement methods is aimed.

It is evident that high accuracy fiber optic detectors are needed to improve uncertainty in the determination of fiber nonlinearity. A good solution for this problem is a fiber optic detector based on the integrating sphere and a mounted InGaAs photodiode. It is capable of measuring high optical power without any external attenuator and therefore offers better repeatability as the number of fiber connections is reduced.

We also demonstrate a method that can be easily used to take into account the effects of dispersion during data analysis by using the Nonlinear Schrödinger equation to model nonlinear phase shift and nonlinear coefficient. These improvements do not modify the basic idea of the direct continuous-wave self-phase modulation method, but are easily implemented to already existing measurement setups. The technique allows also flexible adjustment of the measured fiber length, wavelength spacing of the dual-frequency signal, fiber dispersion and launched optical power. Therefore, the method could possibly be exploited with other types of fibers, if appropriate dispersion equations are selected. However, this can significantly affect the uncertainty component arising from dispersion effects. It is also reasonable to expect that the same approach would improve the accuracies of other techniques used to measure the nonlinearity of optical fibers.

TABLE 2. RESULTS FOR TWO SMFS WITH DIFFERENT CORE AND CLADDING COMPOSITIONS.

	Nonlinear coefficient n_2/A_{eff} ($10^{-10} \cdot \mathrm{W}^{-1}$)		
	Dispersion taken into account	Dispersion neglected	Difference for analysis techniques (%)
Fiber 1 sample 500 m	2.78 ± 0.03	2.85	2.27
Fiber 1 sample 1000 m	2.74 ± 0.03	2.74	0.12
Fiber 2 sample 500 m	2.91 ± 0.03	2.97	1.99
Fiber 2 sample 1000 m	2.93 ± 0.03	2.93	-0.15

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