Nonlinearity measurement of optical fibers using continuous-wave self-phase modulation method

Laboratory exercise
**Introduction**

The recent development of the telecommunications networks has increased the need of the optical signal processing. The link lengths have grown to thousands of kilometers with no need to convert optical signals back and forth to electric form, and transmission speeds of terabits per second are today feasible. This ever-growing demand for the high speed communication has forced to use higher bit rates and transmission powers.

By increasing the capacity of the optical transmission line, which can be done by increasing channel bit rate, decreasing channel spacing or the combination of both, the fiber nonlinearities come to play more decisive role. Therefore the nonlinear effects have become even more important since the development of erbium-doped fiber amplifier (EFDA) and wavelength division multiplexed (WDM) systems.

The origin of the nonlinearities is the refractive index of the optical fiber, which is varying with the intensity of optical signal. This intensity-dependent component of the refractive index includes several nonlinear effects, and becomes significant when high powers are used. Although the individual power in each channel may be below the level needed to produce nonlinearities, the total power summed over all channels can quickly become significant. The combination of high total optical power and large number of channels at closely spaced wavelengths is a source for many kinds of nonlinear interactions.

For the above-mentioned reasons, it is important to understand nonlinear effects of optical fiber and to be able to measure them. Several different nonlinear effects have been used to measure the nonlinear coefficient or the nonlinear refractive index of the optical fibers. The earliest measurements of nonlinear refractive index in silica fibers were carried out in 1978 [1]. The results from this experiment were used almost exclusively in most studies of the nonlinear effects in optical fibers in spite of the fact that the nonlinear refractive index normally varies from fiber to fiber.

The growing importance of nonlinear effects in optical communication systems revived interest in the measurements of the nonlinear refractive index during 1990s, especially because fiber manufacturers are often required to specify its numerical value for their fibers. Nonlinear coefficient of the optical fiber may become an important parameter, when new optical long-haul transmission lines and networks are being deployed. Therefore, several different techniques have been proposed to measure the nonlinear refractive index or nonlinear coefficient of various kinds of optical fibers.

The aim of this work is to measure the nonlinear coefficient of a standard single-mode fiber (SMF) using continuous-wave self-phase modulation (CW SPM) method. This task includes an investigation of some factors affecting the measurement results. The applied method is one of the strongest candidates to be standardized by International Telecommunications Union (ITU). The CW SPM method itself is based on an optical dual-frequency signal that will develop sidebands due to self-phase modulation (SPM). The laboratory work is also hoped to clarify the theory behind different nonlinear phenomena.

The measurement technique is actually used in a similar kind of form for determination of the nonlinear coefficient of optical fibers at the Metrology Research Institute, Helsinki University of Technology.
2 Fiber Optics

2.1 Introduction

The invention of low-loss silica fibers gave a revolutionary impact to the research of the optical communications. Optical fibers have significant advantages compared to the conventional transmission lines. Silica-glass fibers have low losses, enormous bandwidth, and capability to realize high speed transmission networks. These advantages make them several orders of magnitudes better compared to conventional copper cables.

2.2 Light Propagation in Optical Fiber

If light propagates in a medium, its speed is reduced. The speed is affected by such factors as purity and structure of the material. The speed of light, \( c \), inside a medium is defined through the refractive index \( n \) as

\[
c = \frac{c_0}{n},
\]

(1)

where \( c_0 = 2.99792458 \times 10^8 \text{ m/s} \) is the speed of light in vacuum [2].

In an optical fiber, light propagates partly in the core and partly in the cladding. Therefore, the propagation constants, \( \beta_i \), of a mode of the fiber satisfy the condition \( k_0 n_{\text{cladding}} < \beta_i < k_0 n_{\text{core}} \), where \( k_0 \) is the wavenumber in vacuum. Instead of the propagation constant of the mode, we can use effective index \( n_{\text{eff}} = \beta_i / k_0 \). The effective index of the mode lies between the indexes of the core and cladding. For the monochromatic wave in a single-mode fiber, the effective index is analogous to the refractive index and it can be replaced in Eq. 1 to obtain the speed of light inside the single-mode fiber.

As the light propagates along the fiber it is attenuated. The output power, \( P_T \), after the length \( L \) will be:

\[
P_T = P_0 e^{-\alpha L},
\]

(2)

where \( \alpha [1/\text{m}] \) is an attenuation constant representing total losses of the fiber, and \( P_0 \) is the input power. It is customary to express \( \alpha_{\text{dB}} \) in units of dB/km. The conversion can be done with a relation:

\[
\alpha = \frac{10 \log_{10} \left( \frac{\alpha_{\text{dB}}}{10} \right)}{1000} \text{ [1/m]}.
\]

(3)

Some common values of \( \alpha \) have been converted to the corresponding normalized units in Table 1.

<table>
<thead>
<tr>
<th>( \alpha_{\text{dB}} ) [dB/km]</th>
<th>( \alpha \cdot 10^{-5} ) [1/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>4.605</td>
</tr>
<tr>
<td>0.25</td>
<td>5.756</td>
</tr>
<tr>
<td>0.50</td>
<td>11.513</td>
</tr>
<tr>
<td>1.00</td>
<td>23.026</td>
</tr>
</tbody>
</table>

Table 1. Converted attenuation constants
The optical power is often given in units of dBm instead of watts. This makes it possible to do relative calculations only by subtracting and adding powers. The dBm-unit is defined as the power related to 1 milliwatt in decibel-units. This relation between W and dBm can be written as
\[
P_{\text{dBm}} = 10 \log_{10} \left( \frac{P[W]}{10^{-3} W} \right).
\]

\[\text{(4)}\]

**Dispersion**

Any effect, causing the different components of the transmitted signal to propagate at different velocities, is called *dispersion*. Dispersion of an optical fiber can be divided in three categories: modal dispersion, chromatic dispersion, and polarization-mode dispersion (PMD).

Modal dispersion is taking place only in multimode fibers. Different modes of the fiber propagate at different velocities. PMD arises from the different velocities of the polarization states in the birefringent fiber. As the fiber is not perfectly circularly symmetric, the two orthogonally polarized modes have slightly different propagation constants.

The origin of the *chromatic dispersion* can be divided into two categories: material dispersion and waveguide dispersion. The material dispersion arises, because the refractive index of the optical fiber is wavelength dependent. Thus, the different wavelengths will travel at different velocities inside the fiber. The waveguide dispersion arises from the different effective indexes for different wavelengths. The power distribution of a mode, between the core and the cladding, is varying as a function of the wavelength. Therefore, the longer the wavelength, the more power in the cladding and the effective index is closer to the refractive index of the cladding. The chromatic dispersion has a crucial role in optical fiber transmission systems and measurements. It can strengthen the effects of nonlinearities severely and limit the achievable transmission lengths in the optical networks.

### 3 Nonlinearities of Optical Fiber

#### 3.1 Introduction

The nonlinear effects can be divided into two categories. The first type arises due the interaction of light waves with phonons. It contains two important nonlinear scattering effects called stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The second category of the nonlinearities contains the effects that are related to the Kerr effect, that is, the intensity dependence on the nonlinear refractive index of the optical fiber. The main effects in this category are self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). The category also contains effects called modulation instability and soliton formation.

These nonlinear effects are characterized and influenced by several parameters, including dispersion, effective area of the optical fiber, overall unregenerated system length, channel spacing in multi-channel systems, the degree of longitudinal uniformity of the fiber characteristics, source linewidth and intensity of the signal. Therefore, at high bit rates such as 10 Gb/s and above and/or at higher transmitted powers, it is important to consider the effect of nonlinearities. In the case of WDM systems, nonlinear effects can become important even at moderate optical powers and bit rates.

**Effective length**

As the signal propagates along the fiber its power decreases because of attenuation. Modeling this effect can be quite complicated, but in practice, a simple model that assumes that the power is constant over a certain
effective length, $L_{\text{eff}}$, has proven to be quite sufficient in estimating the effect of nonlinearities. Most of the nonlinear effects occur in the beginning of the fiber. The principle of effective length is presented in Fig. 1. On the left side, power is attenuated along the whole fiber length, and on the right side the power is assumed to be constant over the certain effective length of

$$L_{\text{eff}} = \frac{1}{P_0} \int_0^L P_0 e^{-\alpha z} dz = \frac{1}{P_0} \left[ -e^{-\alpha z} \right]_0^L = \frac{1}{\alpha} \left( e^{-\alpha L} - 1 \right) = \frac{1 - e^{-\alpha L}}{\alpha},$$

where $\alpha$ is the attenuation constant.

![Figure 1](image)

Figure 1. (a) Propagating power along the fiber length $L$ and (b) the corresponding model for effective length.

### 3.2 Nonlinear Refractive Index

#### 3.2.1 Introduction

Nonlinear interactions between light and silica fiber start to arise, when high powers are used. The response of any dielectric material to light becomes nonlinear for intense electromagnetic fields. Several nonlinear effects influence the propagation of light. The total polarization $\mathbf{P}$ is not linear with respect to the electric field $\mathbf{E}$ but it can be written as

$$\mathbf{P} = \varepsilon_0 \left( \chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} \cdot \mathbf{E} \cdot \mathbf{E} + \chi^{(3)} \cdot \mathbf{E} \cdot \mathbf{E} \cdot \mathbf{E} + \cdots \right),$$

where $\varepsilon_0$ is the vacuum permittivity and $\chi^{(j)} (j = 1, 2, \ldots)$ is $j$th order susceptibility. The linear susceptibility $\chi^{(1)}$ represents the dominant contribution to $\mathbf{P}$. It is included in the refractive index $n$ and the attenuation constant $\alpha$. The second order susceptibility $\chi^{(2)}$ is responsible for nonlinear effects such as second-harmonic generation and sum-frequency generation. However, these phenomena arise from the lack of inversion symmetry of the propagation medium molecules. As $\text{SiO}_2$ is a symmetrical molecule, the second-order susceptibility normally vanishes. [3]

The lowest-order nonlinear effects in the optical fibers originate from the third-order susceptibility $\chi^{(3)}$, which is responsible for such phenomena as third-harmonic generation, four-wave mixing and nonlinear refraction. Most of the nonlinear effects in optical fiber arise from the nonlinear refraction, a phenomenon referring to the intensity dependence of the refractive index. The relation between the refractive index $n$, intensity $I$ and power $P$ is
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\[
n = n_0 + n_2 I = n_0 + \left( \frac{n_2}{A_{\text{eff}}} \right) P,
\]

(8)

where the first term \(n_0\) is the wavelength-dependent part of the refractive index and \(A_{\text{eff}}\) is the effective area of the optical fiber. The second term, nonlinear refractive index, \(n_2\), collects up intensity-dependent nonlinear effects [5]. The most interesting effects of this group are self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). Because all of the above-mentioned effects are intensity-dependent and optical fiber has relatively low value of nonlinear susceptibility \(\chi^{(3)}\), these effects are visible only at high powers.

The nonlinear coefficient is defined as \(n_2/A_{\text{eff}}\) [5]. Therefore, it can be measured without knowing the effective area of the optical fiber. However, the impact of the nonlinear effects depends also on the effective area. If the effective area is increased, then the influence of the intensity dependent nonlinear effects is reduced.

In literature, the nonlinear coefficient has two different notations. The relation between the often applied nonlinear parameter, \(\gamma\), and nonlinear refractive index, \(n_2\), is

\[
\gamma = \frac{\omega_0 n_2}{c_0 A_{\text{eff}}} = \frac{2\pi n_2}{\lambda_0 A_{\text{eff}}},
\]

(9)

where \(\omega_0\) represents the angular frequency of the light wave, \(c_0\) is the speed of light in vacuum, \(\lambda_0\) is the wavelength in vacuum and \(A_{\text{eff}}\) is the effective area of the optical fiber.

Typically, measured values for nonlinear refractive index \(n_2\) are found to vary in the range 2.2 - 3.9\times10^{-20} \text{m}^2/\text{W} for silica [3, 6]. Such large variation in the values of \(n_2\) can be explained by different dopants in the fiber core and cladding, such as GeO\(_2\) and Al\(_2\)O\(_3\).

### 3.2.2 Self-Phase Modulation (SPM)

Self-phase modulation (SPM) induces phase shift that is proportional to the optical power. It can be understood as a modulation, where the intensity of the signal modulates its own phase. In the SPM different parts of the pulse undergo optical power dependent phase shifts, leading to broadening of the pulse spectrum.

**Nonlinear pulse propagation**

Pulse propagation in fibers can be described by nonlinear Schrödinger equation (NLS) [3]:

\[
\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + i \beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i \gamma |A|^2 A,
\]

(10)

where \(A\) is the pulse amplitude that is assumed to be normalized such that \(|A|^2\) represents the optical power. NLS equation includes the effects of fiber losses through \(\alpha\), chromatic dispersion through \(\beta_1\) and \(\beta_2\), and fiber nonlinearity through \(\gamma\).

The dispersion parameter, \(D\), is related to propagation constants \(\beta_1\) and \(\beta_2\) by the relation [3]:
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\[
D = \frac{d\beta_2}{d\lambda} = -\frac{2\pi c_0^2}{\lambda^2} \beta_2 \approx \frac{\lambda}{c_0} \frac{d^2 n}{d\lambda^2},
\]

(11)

where \(c_0\) is the speed of light in vacuum, \(\lambda\) is the wavelength in vacuum, and \(n\) is the refractive index.

**Nonlinear phase shift**

The group velocity dispersion can be neglected for relatively long pulses \((T_0 > 100\text{ps})\) with a large peak power \((P_0 > 1\text{W})\) [3]. As a result, the term \(\beta_2\) can be set to zero in Eq. 10. Now, the SPM gives rise to an intensity-dependent nonlinear phase shift \(\phi_{\text{SPM}}\).

First, normalized amplitude, \(U\), is defined by [3]

\[
A(z, T) = \sqrt{P_0} e^{-\alpha/2} U(z, \tau),
\]

(12)

where \(A\) is the slowly varying amplitude of the pulse, \(P_0\) is the peak power of the incident pulse, \(\alpha\) represents losses, and \(\tau\) is the normalized time scale proportional to the input pulse width \(T_0\). The \(\tau\) is defined as

\[
\tau = \frac{T}{T_0} = \frac{t - z/v_g}{T_0},
\]

(13)

where \(v_g\) is the group velocity, and \(T\) is measured pulse width in a frame of reference moving with the pulse at group velocity after pulse has propagated time \(t\) and distance \(z\) in the fiber.

Now, the pulse-propagation equation [3] can be written with normalized amplitude as

\[
\frac{\partial U}{\partial z} = \frac{1}{L_{\text{NL}}} \left| U \right|^2 U,
\]

(14)

where \(\alpha\) accounts for fiber losses. The nonlinear length \(L_{\text{NL}}\) is defined as [3]

\[
L_{\text{NL}} = \frac{1}{\gamma P_0},
\]

(15)

where \(P_0\) is the peak power and \(\gamma\) is related to nonlinear refractive index as in Eq. 9. Equation 14 can be solved directly to obtain the general solution

\[
U(L, T) = U(0, T)e^{\phi_{\text{NL}}(L, T)}.
\]

(16)

Where \(U(0, T)\) is the field amplitude at \(z = 0\) and nonlinear phase shift is
\[ \varphi_{NL}(L,T) = |U(0,T)|^2 \left( \frac{L_{eff}}{L_{NL}} \right) \]

with the effective length \( L_{eff} \) defined in Eq. 5.

Equation 16 shows that SPM gives rise to the intensity-dependent phase shift but the pulse shape remains unaffected. The nonlinear phase shift \( \varphi_{NL} \) increases with fiber length. In the absence of fiber losses \( \alpha = 0 \) and \( L_{eff} = L \), the maximum phase shift \( \varphi_{MAX} \) occurs at the pulse center located at \( T = 0 \). With \( U \) normalized such that \( |U(0,0)| = 1 \), it is given by

\[ \varphi_{MAX} = \frac{L_{eff}}{L_{NL}} = \gamma P_0 L_{eff}. \]

The effect of SPM to an optical signal propagating along the fiber is presented in Fig 2. The frequency chirp and dispersion induce distortion to output signal.

3.3 Nonlinear Scattering

Nonlinear scattering contains two important phenomena caused by interaction of light with phonons. The first one is stimulated Brillouin scattering (SBS) and the second one is stimulated Raman scattering (SRS).

SBS occurs when an intense light beam scatters from an acoustic phonon. SRS takes place when optical phonon is involved. Different phonons cause some basic differences between the phenomena. A fundamental difference is that SBS occurs mainly in the backward direction while SRS can occur in both directions. We limit our study only to SBS, because the threshold power of the SRS is considerably higher compared to the threshold power of the SBS.

Stimulated Brillouin scattering (SBS) can be considered classically as a nonlinear interaction between the input field and Stokes fields through an acoustic wave. The power of the input field generates the acoustic wave through the process of electrostriction. The acoustic wave in turn modulates the refractive index of the propagation medium. This power-induced index grating scatters the incoming light through...
Bragg reflection. Scattered light is downshifted in frequency, because of the Doppler shift associated with a grating moving at the acoustic velocity \[3\]. The principle of SBS is presented in Fig. 3.

![Figure 3. Principle of SBS.](image)

The SBS takes place in a very narrow bandwidth of 20MHz at 1.55µm \[4\]. The interaction produces the Stokes wave propagating to a direction opposite to the pump wave. The back scattered power caused by the SBS has been presented in Fig. 4. The peak at lower wavelength is not frequency shifted since it is caused by the Rayleigh scattering and the reflections of the connectors and splices. The power, back scattered due to SBS, is frequency shifted to higher wavelength, because of the Doppler shift.

![Figure 4. Spectrum of reflected light from 500m long SMF with input power of 25.7dBm](image)

4 Effective Area of Optical Fiber

All the nonlinear effects depend on intensity distribution inside the optical fiber. However, the field is not uniformly distributed inside a single-mode fiber. It also propagates partly outside of the core of the fiber. If we use the uniform relationship for the intensity

\[
I = \frac{P_{\text{meas}}}{A_{\text{core}}},
\]

we will underestimate the value on the axis of the fiber and overestimate the value near core-cladding interface. The effective area \(A_{\text{eff}}\) has been defined for the purposes of calculating nonlinear effects and characterizing fibers with standardized parameters. It is a single value that can be used to replace the \(A_{\text{core}}\) in
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Eq.19 for calculating the optical intensities. International Telecommunication Union (ITU) has standardized the concept of effective area $A_{\text{eff}}$ [5]. The definition is:

$$A_{\text{eff}} = \frac{2\pi \int_0^\infty |E(r)|^2 r dr}{\int_0^\infty |E(r)|^4 r dr} = \frac{2\pi \int_0^\infty I(r) r dr}{\int_0^\infty I(r)^2 r dr}$$

(20)

where $E(r)$ is the amplitude and $I(r)$ is the intensity of the fundamental mode at radius $r$ from the axis of the fiber. Typically, $A_{\text{eff}}$ can vary in a range of 20-100$\mu$m$^2$ in the 1.5-$\mu$m region depending on the fiber design [3].

The concept of the effective area can be adapted to fibers regardless of their refractive index profile. In Fig. 5, two different refractive index profiles and their intensity distribution are shown.

Figure 5. Refractive index profile and intensity distribution of (a) step-index, (b) depressed cladding

For conventional step-index fibers, we can approximate the effective area by using the Gaussian function of radius $w$ in its $e^{-1}$ amplitude points. This approximation is accurate only for standard single-mode fibers (ITU-T G.652) and cut-off shifted fibers (ITU-T G.654) near the cut-off of the LP$_{11}$-mode. At much longer wavelengths, the Gaussian approximation is not valid. In this simplified case the effective area can be written as [5]:

$$A_{\text{eff}} = \pi w^2 (\lambda),$$

(21)

$$w(\lambda) = \frac{\text{MFD}(\lambda)}{2},$$

(22)

where MFD($\lambda$) is the Petermann-II mode-field diameter of the fiber at wavelength $\lambda$.

5 Measurement of Nonlinear Coefficient

5.1 Introduction

The nonlinear coefficient $n_2/A_{\text{eff}}$ is covering a large variety of different nonlinear effects. Increasing powers in WDM systems have made its accurate determination very important. Also fiber manufacturers might need to specify the values of $n_2/A_{\text{eff}}$ of their fibers.

Several different nonlinear effects have been proposed to be used for measuring the nonlinearities. Most commonly self-phase modulation, cross-phase modulation, four-wave mixing, and modulation instability are used. Some of the methods applied to determine the nonlinear coefficient are based on pulsed lasers instead
of continuous wave sources. This will set high demands for determination of the pulse duration and its peak power.

5.2 Continuous Wave Self-Phase Modulation Method (CW SPM)

The continuous wave self-phase modulation (CW SPM) method to determine the nonlinear coefficient of optical fiber was first introduced in 1993 [7]. It removed uncertainties about initial pump powers by using continuous wave laser sources. Since, use of dual-wavelength CW SPM-method to determine $n_2$ of the various kinds of optical fibers has been reported in several publications. For example standard single-mode, dispersion compensated and dispersion shifted fibers have been measured [8, 9, 10].

The method itself is based on the measurement of the nonlinear phase shift induced by SPM. The phase-shift can be measured indirectly from the intensity peak heights of the dual wavelength source and the first harmonics that are generated by SPM. Neglecting the dispersion, a dual frequency optical beam out from the fiber can be expressed as:

$$U(L,T) = [E_1 \sin(\omega_1 T) + E_2 \sin(\omega_2 T)]e^{i\int E_1 \sin(\omega_1 T) + E_2 \sin(\omega_2 T) \varphi_{SPM}}. \quad (23)$$

Where $U(L,T)$ is expressed in terms of the normalized amplitude. From this equation, as presented in Ch. 3.2.2, the maximum phase shift $\varphi_{SPM}$ can be obtained:

$$\varphi_{SPM} = \frac{L_{eff}}{L_{NL}} = \frac{2\omega_0}{cA_{eff}} \frac{n_2}{L_{eff}} P_{AVG}, \quad (24)$$

where $P_{AVG}$ is the average power of the dual wave signal, $L_{eff}$ is the effective length of the fiber, $n_2/A_{eff}$ is the nonlinear coefficient, $A_{eff}$ is the effective area of the optical fiber, and $\omega_0$ is the center frequency of the dual wavelength signal.

To determine the nonlinear coefficient of the optical fiber, the nonlinear phase shift $\varphi_{SPM}$ and the corresponding power are measured experimentally. The nonlinear phase shift is measured in spectral domain. As the electric field is a periodic function in time, its spectrum is discrete, consisting of harmonics of the beat frequency ($\omega_2 - \omega_1$) as presented in Fig. 6. The nonlinear phase shift can be determined from the shape of the spectrum. Therefore, it is possible only to measure the relative heights of the spectral components. Equation 25 gives us the ratio of spectral intensities of the fundamental wavelengths to the first-order sidebands

$$\frac{I_0}{I_1} = \frac{J_0^2 \left( \frac{\varphi_{SPM}}{2} \right)}{J_1^2 \left( \frac{\varphi_{SPM}}{2} \right)} + \frac{J_1^2 \left( \frac{\varphi_{SPM}}{2} \right)}{J_2^2 \left( \frac{\varphi_{SPM}}{2} \right)}. \quad (25)$$

Here $I_0$ is the intensity of the fundamental wavelength and the $I_1$ the intensity of the first-order sideband. $J_n$ is the $n$th order Bessel function. Now, the phase shift is only a function of $I_1/I_0$, which can be easily measured.
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Figure 6. Dual-frequency signal ($\omega_1$ & $\omega_2$) will generate new frequencies due to SPM. These frequencies are determined by the frequency of the beat signal ($\omega_2 - \omega_1$).

In Fig. 7, the intensity ratio $I_0/I_1$ (Eq. 25) was measured at different fiber input powers and the corresponding phase shifts were calculated using Eq. 24. It is also possible to calculate the nonlinear coefficient from the angular coefficient of the linear fit to the measurement points. Then the results are analyzed from the linear part of the measured phase-shift curve. The measured values can be fitted to line by the following relation, obtained from the Eq. 24., as

$$
\frac{n_2}{A_{\text{eff}}} = \frac{\lambda_0}{4\pi L_{\text{eff}}} \left( \frac{\phi_{\text{SPM}}}{P_{\text{AVG}}} \right) = \frac{\lambda_0}{4\pi L_{\text{eff}}} k_{ac}
$$

where $\lambda_0$ is the center wavelength in vacuum and $L_{\text{eff}}$ is the effective length. The slope coefficient $k_{ac}$ can be determined from the linear region of the function $\phi_{\text{SPM}}(P_{\text{AVG}})$. The determination of the nonlinear coefficient $n_2/A_{\text{eff}}$, from the group of measurement points, eliminates partly possible parasitic errors occurring at one individual measurement point.

Figure 7. (a) Measured intensity ratio $I_0/I_1$ for 500m SMF and (b) the corresponding phase shift for each power.
6 References


