NONLINEAR REFRRACTIVE INDEX OF STERLITE'S G.652.D OPTICAL FIBER

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Abstract
We present nonlinear refractive measurement method and results for Sterlite’s G.652.D optical fiber. The nonlinear index was found to be about $2.19 \times 10^{-20}$ m$^2$/W at 1550 nm and the nonlinear coefficient was found to be about 1.12 (W km)$^{-1}$ at 1550 nm.

Keywords
Optical fiber, nonlinearity, self phase modulation
1. Introduction

Nowadays, the fiber optics is employed not only for creation of global and local computer networks but also for a private network's needs. At the same time, the rapid increase in the power launched into the optical fiber causes phenomena such as nonlinear optical effects. It is well known that nonlinearities are playing a decisive role in currently developing high-bit-rate transmission systems that use non-return-to-zero formats and include wavelength-division multiplexed systems. Concurrently, the idea of dispersion management in the transmission system has been useful not only for upgrading the currently installed system but also for ultrahigh-bit-rate transmission. These systems may incorporate different types of fibers, including standard telecommunication fiber (G652.D). To accommodate effects of nonlinearities in system budget, one must know the nonlinear coefficient, \( n_2 \), for fibers used and the effect of constituents of the fiber on nonlinearity must be readily determinable. Therefore there is increasing interest in accurate measurement of the nonlinear refractive indices of fibers of different compositions [1-5].

In the current application note, we present a method to measure the nonlinear refractive index that is based on self-phase modulation and present the nonlinearity measurement results for Sterlite's G.652.D optical fiber.

2. Theoretical background

An optical fiber is characterized by nonlinear properties; the most significant of its parameters being the nonlinear refraction index and the effective cross-section area, \( A_{\text{eff}} \) [1]. The majority of nonlinear optical effects arise in a fiber because of high light intensities due to refractive index dependence on the intensity:

\[
n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{\text{eff}}}
\]

where \( n_0 \) is the linear refractive index, \( n_2 \) is the nonlinear refractive index, \( I \) is the light radiation intensity, \( P \) is the maximum radiated power, \( A_{\text{eff}} \) is the effective area given by:

\[
A_{\text{eff}} = \frac{\left[2\pi \int_{-\infty}^{\infty} E^2 r dr\right]^2}{\left[2\pi \int_{-\infty}^{\infty} E r dr\right]^2}
\]

where \( E \) is the mode field and \( r \) is the radial parameter. Another parameter characterizing the optical fiber nonlinearity is the nonlinear phase shift, which depends on the optical fiber effective length \( L_{\text{eff}} \) defined as

\[
L_{\text{eff}} = \frac{1 - \exp(\alpha L)}{\alpha}
\]

The phase maximum is found from the relationship:

\[
\Phi_{\text{SM}} = \frac{L_{\text{eff}}}{L_{\text{NL}}} = \gamma P_{\text{in}} L_{\text{eff}}
\]

where \( L_{\text{NL}} \) is the optical fiber nonlinear length, \( P_{\text{in}} \) is the power, \( \gamma \) is the nonlinear coefficient, which is expressed as,

\[
\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{\text{eff}}}
\]
When a continuous wave dual frequency beat signal is used as a pump signal, the resultant spectrum is discrete, consisting of harmonics of the beat frequency as shown in Fig. 1. The nonlinear phase shift induced in the optical fiber by self phase modulation (SPM) effect is determined from the discrete shape of the spectrum, i.e., relative ratio of the spectral components given by Eq. (6) [2-5]:

\[
\frac{l_0}{l_1} = \frac{j_0^2 (\frac{\Theta_{\text{spm}}}{2}) + j_1^2 (\frac{\Theta_{\text{spm}}}{2})}{j_2^2 (\frac{\Theta_{\text{spm}}}{2}) + j_1^2 (\frac{\Theta_{\text{spm}}}{2})}
\]

where \(l_0\) and \(l_1\) are intensities of the zeroth and first order harmonics (Fig. 1) and \(J_n\) is the Bessel function of \(n\)th order.

Fig. 1. Typical harmonics of the beat frequency.

3. Measurement method

The experimental arrangement to measure the nonlinear refractive index by continuous wave-SPM (cw-SPM) method is shown in Fig. 2. Outputs of two distributed-feedback laser sources operating at wavelengths \(\lambda_1\) and \(\lambda_2\), which are as close as possible are polarized (PC) and passed though the band pass filter (BPF, \(\sim 4\) nm at \(1550\) nm) to filter out unwanted variations that are out of the SPM band. This signal is then amplified by using the Er-doped amplifier (EDFA) and applied to the fiber under test (FUT) as shown in Fig. 2. Resulting output spectrum is passed through the attenuator (ATT) to protect the optical spectrum analyzer (OSA) and measurements are taken at the OSA.
Step-by-step measurement method for the nonlinear refractive index is described as follows. It is noted that explanation is according to instruments available in the Photonics Laboratory at Center of Excellence.

(i) Arrange the experimental setup as shown in Fig. 2. It is very important to use the attenuator before the OSA to prevent damage due to accidental raise in the optical power. An operator should wear the protective goggle.

(ii) Note the length of the optical fiber under test (L). It is typically <= 1 km.

(iii) Set two laser diode wavelengths at less than 1 nm apart in the vicinity of 1550 nm.

(iv) Set the required gain in the EDFA. Typical gain giving the output of around 10-20 mW of total power is enough for the experiment using standard fibers.

(v) Turn ON two laser diodes and EDFA. Vary the attenuator to adjust the observable OSA power. Typical attenuator will have 10–20 dB attenuation.

(vi) Adjust two polarization controllers (PC) one by one so that measurable sidebands are obtained at the OSA.

(vii) Note the output power of EDFA (= P

(viii) Measure peak power of the zero and first harmonics.

(ix) Determine using Ø Eq. (6).

(x) With known attenuation (in dB/km) of the fiber at 1550 nm (= αdB), and Aeff at λ, determine n2 by using following relationships [2, 3]:

\[
L_{\text{eff}} = \frac{1 - \exp\left[\frac{\log_{10}(\alpha_{dB}) \times 1000}{\log_{10}(\alpha_{dB/10})}\right]}{\log_{10}(\alpha_{dB/10})} \text{ km} \quad (7)
\]

\[
n_2 = \frac{\lambda}{4\pi} \frac{A_{\text{eff}}}{L} \left( \frac{\Phi_{\text{SPM}}}{P_{\text{in}}} \right) \quad (8)
\]

\[
\lambda = \frac{\lambda_1 + \lambda_2}{2} \quad (9)
\]

As a note on units used in above equation, the power is in W, A_{\text{eff}} is in m², L and wavelength (λ) are in m. To convert the power in dBm to Watts, following conversion formula is used:
If the fiber length is more than 20 Km, then $L$ is replaced by $L_{\text{eff}}$ in Eq. (8).

(xi) Repeat steps (vii) to (x) for different powers.

4. Results and discussion

Fiber used for nonlinearity measurement had optical properties and length as listed in Table I.

<table>
<thead>
<tr>
<th>Table I. Optical fiber parameters</th>
</tr>
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<tbody>
<tr>
<td></td>
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<tr>
<td>G.652D</td>
</tr>
<tr>
<td>Attenuation at 1550 nm (dB/km)</td>
</tr>
<tr>
<td>Length of the fiber (km)</td>
</tr>
<tr>
<td>$A_{\text{eff}}$ (μm$^2$)</td>
</tr>
<tr>
<td>Dispersion at 1550 nm (ps/km.nm)</td>
</tr>
<tr>
<td>MFD at 1550 nm (μm)</td>
</tr>
</tbody>
</table>

The optical fiber sample of length 1 km was used in the experimental setup shown in Fig. 2. The resultant output pattern was recorded by using the OSA as shown in Fig. 3. It showed the beat pattern having two major peaks surrounded by two minor peaks. It is important to use small length of fiber (<= 1 km) to avoid dispersion seriously affecting the beat pattern of the output spectrum. Observations noted down from the spectrum are listed in Table II.

![Output power spectrum](image)

**Fig. 3. Output power spectrum.**
Table II. Observations from the beat pattern of Fig. 3. $P_{in}$ is the input power applied to the fiber under test.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>$P_{in}$ (dBm)</th>
</tr>
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<tbody>
<tr>
<td>1549.902 nm</td>
<td>10.13</td>
</tr>
<tr>
<td>1550.07 nm</td>
<td>-53.144</td>
</tr>
<tr>
<td>1550.238 nm</td>
<td>-51.162</td>
</tr>
<tr>
<td>1550.408 nm</td>
<td>10.8</td>
</tr>
<tr>
<td>Ø (radians)</td>
<td>-12.814</td>
</tr>
<tr>
<td>n$_2$ (m$^2$/W)</td>
<td>0.024</td>
</tr>
<tr>
<td>Average n$_2$ (m$^2$/W)</td>
<td>2.31×10$^{-20}$</td>
</tr>
</tbody>
</table>

The mean value of nonlinear refractive index (n$_2$) was found to be 2.19×10$^{-20}$ m$^2$/W (standard deviation = 0.14×10$^{-20}$). This value is quite comparable to the known nonlinear refractive index of about (2.22 to 2.45)×10$^{-20}$ m$^2$/W for commercial single mode optical fibers [5]. The nonlinear coefficient can be calculated from Eq. (5), and its value was found to be 1.12 (W km)$^{-1}$.

Approximate value of n$_2$ can also be determined by using the empirical equation [2]:

$$n_2 = 2.16 \times 10^{-16} + 0.033 \times 10^{-16} C \text{ cm}^2$/W (11)

where C is the molar concentration of GeO$_2$ (in %) in the optical fiber core. Using a typical value of C = 3.36 mol% for Sterlite's G652.D fiber, the nonlinear refractive index value was calculated to be 2.27×10$^{-20}$ m$^2$/W, which is quite closer to the measured value.

5. Conclusion

The nonlinear refractive index of Sterlite's G652.D optical fiber was measured experimentally and it was found to be 2.19×10$^{-20}$ m$^2$/W at 1550 nm. The nonlinear coefficient, γ, was found to be 1.12 (W km)$^{-1}$.

References:


