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Direct experimental measurement of SRS-induced spectral tilt in multichannel multispan communication systems

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Abstract. **Nonlinear SRS-induced tilt of the spectrum of a multichannel DWDM signal is studied experimentally in standard single-mode fibreoptic communication lines. It is found that at a fixed spectral bandwidth and total power the nonlinear SRS tilt is independent of the number of channels, radiation source type, and the initial tilt (positive or negative). In a multispan line consisting of identical spans the total nonlinear tilt of the spectrum (in dB) is proportional to the number of spans, spectral width and total power.**

Keywords: *DWDM, stimulated Raman scattering, Raman-induced tilt, fibreoptic communication line.*

20. Introduction

In multichannel communication systems with dense wavelength division multiplexing (DWDM systems) the stimulated Raman scattering (SRS) leads to enhancement of the signals in long-wavelength channels at the expense of the energy of short-wavelength ones [1–3]. As a result, the uniform spectrum of the radiation power at the input of a communication line becomes nonuniform after propagating through the fibre: the power of long-wavelength channels becomes greater than that of the short-wavelength channels. Quantitatively this nonlinear effect may be characterised by the value of skewness or tilt of the output spectrum. The development of modern 80- and 40-channel high-rate communication systems [4–7] (total rate up to 3.2 Tbit s^{-1}) requires precise information about the dependence of the nonlinear spectral tilt on the parameters of the communication line.

Many publications are devoted to the investigation of SRS in fibreoptic communication lines [8–13]; however, the major attention in them is focused on the study of SRS spectrum in the vicinity of the SRS-gain maximum, when the frequency difference between the interacting waves is nearly equal to 13 THz.

This paper presents the results of direct experimental studies of the nonlinear tilt of the spectrum, caused by the SRS interaction of optical signals separated by frequency difference less than or equal to 4 THz. It is shown that in calculations of the SRS-induced tilt in DWDM communication systems the triangle approximation of SRS gain spectrum is applicable even in the presence of the initial linear positive or negative tilt of the spectrum.

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21. Theory of SRS-induced tilt

Theoretical analysis of Raman-induced tilt of the spectrum is given in [1], it is also described in [2, Ch. 8]. Following [1], we consider a system of N spectral channels, simultaneously propagating through a single-mode fibre. Assume that all channels fall within the Raman gain spectral range, for which the approximation of linear dependence of the gain $g_{\rm R}$ on the frequency detuning (i.e., the frequency separation $\Delta\nu_{\rm ch}$ between the interacting channels) is applicable. Let the wavelength be minimal in channel 1 and maximal in channel N, the rest of the channels being uniformly distributed over the spectrum. Then for the interaction of channels the following set of ordinary differential equations can be derived [1–3]:

$$\frac{{\rm d}P_n(z)}{{\rm d}z} + \alpha_{\rm e}P_n(z) + C_{\rm R}P_n(z)\sum_{m=1}^{N}(m-n)P_m(z) = 0, \qquad (1)$$

where $P_n(z)$ is the power in the nth channel; $C_{\rm R} = S_{\rm R}\Delta\nu_{\rm ch}/(2A_{\rm eff})$ is the Raman gain of the adjacent spectral channel; $S_{\rm R} = {\rm d}g_{\rm R}/{\rm d}\nu$ is the tilt of the gain spectrum; $A_{\rm eff}$ is the mode area; $\alpha_{\rm e}$ is the loss coefficient of the signal in the optical fibre (in km^{-1}). It is assumed that the ratio of frequencies in channels $\nu_n/\nu_m \approx 1$, and the random change of polarisation is taken into account.

The general solution of Eqns (1) was obtained in [1] and has the form:

$$P_n(z) = \frac{P_n(0)P_{\rm t}\exp(-\alpha_{\rm e}z)\exp[C_{\rm R}P_{\rm t}(n-1)L_{\rm eff}]}{\sum_{m=1}^{M}P_m(0)\exp[(m-1)C_{\rm R}P_{\rm t}L_{\rm eff}]}, \qquad (2)$$

where $P_{\rm t} = \sum_{m=1}^{M}P_m(0)$ is the total power of the signals in all spectral channels; $L_{\rm eff} = [1-\exp(-\alpha_{\rm e}L)]/\alpha_{\rm e}$ is the effective length of the fibre; L is the length of the line. Rewriting Eqn (2) in logarithmic units (dB and dBm) we obtain

$$p_n(L) = p_n(0) - \alpha L + 10\lg\frac{P_{\rm t}}{\sum_{m=1}^{M}P_m(0)\exp[(m-1)C_{\rm R}P_{\rm t}L_{\rm eff}]}$$

$$+ (n-1)C_{\rm R}P_{\rm t}L_{\rm eff}(10\lg{\rm e}), \qquad (3)$$

where $p_n = 10\lg P_n$; $\alpha = 10\alpha_{\rm e}\lg{\rm e} = 4.3\alpha_{\rm e}$ is the loss coefficient (in dB km^{-1}).

Let us define the value of the SRS tilt as the difference between the output powers (in dB) of the extreme channels, $\Delta p_{M,1} = p_M(L) - p_1(L)$, and the increment of the SRS tilt as the difference between the tilt values at the input and at the out-

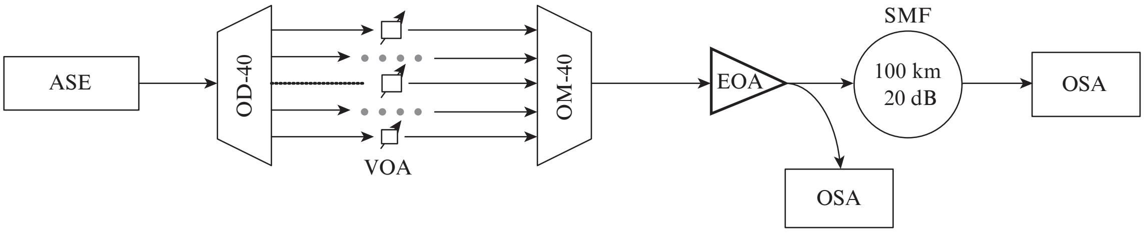

Figure 1. Schematic diagram of the experimental setup for measuring the SRS tilt in optical fibres in the DWDM system: (ASE) source of amplified spontaneous emission; (OD-40) 40-channel demultiplexer; (VOA) variable optical attenuators; (OM-40) 40-channel multiplexer; the SMF fibre 100 km long with losses 20 dB; (EOA) erbium optical amplifier; (OSA) optical spectrum analyser.

put of the line, $\delta(\Delta p_{M,1}) = p_M(L) - p_1(L) - [p_M(0) - p_1(0)]$. From Eqn (3) one can derive a simple expression for the increment of SRS-induced tilt:

$$\delta(\Delta p_{M,1}) = \chi_{\mathrm{R}} \Delta \nu_{M,1} L_{\mathrm{eff}} P_{\mathrm{t}}, \quad (4)$$

where $\chi_{\mathrm{R}} = 4.3 S_{\mathrm{R}}/(2A_{\mathrm{eff}})$ is the nonlinear parameter of the fibre, which may be referred to as the tilt coefficient.

Three important consequences follow from the simple formula (4):

(i) Under the condition that the total power P_{t} and the frequency interval between the extreme channels $\Delta \nu_{M,1}$ are conserved, the increment of the tilt does not depend on the number of channels.

(ii) The increment of the tilt (in dB) linearly depends on the total power (in W).

(iii) The increment of the tilt does not depend on the initial tilt of the spectrum.

22. Experimental setup

The schematic diagram of the experimental setup is presented in Fig. 1. To model the multichannel DWDM signal we used a device comprising a broadband source of amplified spontaneous emission (ASE) and a special unit producing a 40-channel signal with controllable power in each channel. The unit for such signal formation comprised a 40-channel demultiplexer (OD-40), 40 variable optical attenuators (VOA) and a 40-channel multiplexer (OM-40). This unit provided formation of a DWDM signal with any required spectral distribution of the signal power over the optical channels (with an error not exceeding 0.1 dB) at the wavelengths from 1529.55 to 1560.61 nm, corresponding to the standard frequency spectrum with the channel frequency spacing of 100 GHz. The erbium optical amplifier (EOA) ensured the necessary power level at the input of the fibre line.

We also used a DWDM signal obtained by multiplexing signals from commercial telecommunication transmitters of various types.

23. Results of experimental studies

As a result of the performed experimental studies, it was found that the spectrum of a DWDM signal at the output of a single-mode fibreoptic line segment is characterised by linear dependence of the power (in dBm) on the wavelength. For example, in Fig. 2 the spectrum of the DWDM signal at the output of a segment of a dispersion-compensating fibre (DCF) is presented. An analogous spectrum was obtained at the output of a standard telecommunication SMF fibre. The character of the output spectrum (uniform tilt) remains the same in the presence of the initial tilt (of any sign) in the spectrum of the input signal. It is shown experimentally that expression (4) for the increment of nonlinear spectral tilt is valid within a wide range of total powers of the DWDM signal (from 0 to 20 dBm), spectral tilts at the line input, spectral bandwidths of the input signal (from 0.1 to 4 THz), channel numbers (from 2 to 40), and for radiation sources of different types (amplified spontaneous emission, DFB lasers with direct modulation of current, DFB lasers with external modulation).

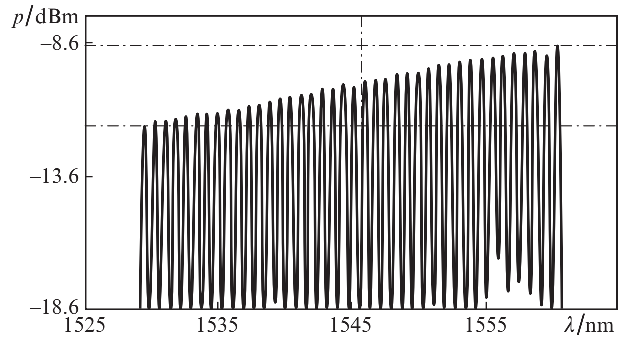

Figure 2. Power spectrum of a DWDM signal at the DCF-fibre-based line output; the total power in the line being 20 dBm.

The dependence of the tilt on the total power P_{t} for two types of fibres is plotted in Fig. 3, the spectral width of the DWDM signal being equal to 3.9 THz. It is seen that the total

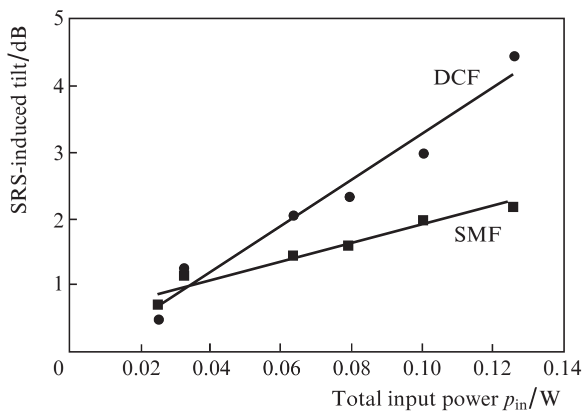

Figure 3. Dependence of the SRS-induced tilt on the total input power p_{in} for the 100 km-long SMF fibre segment and the segment of DCF fibre, compensating the dispersion introduced by the 100-km segment of the SMF fibre.

tilt (in dB) of the output spectrum in the SMF fibre consists of the nonlinear part, depending on the power (SRS-tilt), and the linear part, independent of power:

$$\Delta p_{out} = p_{max} - p_{min} = \Delta p_{lin} + \Delta p_R = 0.55 + 11P_t, \quad (5)$$

where Δp_R is the nonlinear SRS-induced tilt and Δp_{lin} is the linear tilt (at $p_{in} = 0$).

In SMF fibres the linear tilt is caused by the spectral dependence of the optical losses. The plot of such a dependence for the fibre used in the experiment is presented in Fig. 4. In the DCF fibre the linear tilt appears to be negligibly small because of the relatively small length of the fibre (10.2 km) and small total attenuation (6.2 dB). Therefore, the total tilt in this case is determined by the SRS-induced tilt:

$$\Delta p_{out} = 34.5P_t. \quad (6)$$

Using Eqn (4) and the experimental dependences (5) and (6), the coefficients of nonlinear tilt were calculated (see Table 1).

Figure 4. Dependence of the optical loss coefficient on the wavelength in the studied telecommunication SMF fibre.

Table 1. SRS-induced tilt coefficients.

Fibre	χ_R/dB THz^{-1} W^{-1} km^{-1}	Effective length/km	Spectral bandwidth/THz
SMF	0.145±0.02	19.5	3.9
DCF	1.1±0.1	8.1	3.9

To study the accumulation (increment) of the spectral tilt from span to span in a multispan line we performed the following experiment using the setup, presented in Fig. 1. A DWDM signal, whose spectrum simulated the spectrum of an amplified DWDM signal from the first span, was applied to the input of the fibre line, modelling the second span of a multispan communication line. The spectrum of the DWDM signal, output from the segment simulating the second span, was used to model the input signal for the third one, etc. Such iterations were repeated up to ten times, which allowed simulation of signal passing through a multispan communication line with the number of spans up to ten and maximal length 1000 km. The total power of the DWDM signal at the input of the line was kept constant. Within the accuracy of measurements, the increment of the tilt was constant and equal to the tilt acquired during the first iteration (at the first span). This fact means that the total tilt in a multispan line grows proportionally to the number of spans, N.

In the experiment we also studied the increment of the tilt in the case when the input signal possesses a negative tilt of the power spectrum. In this case the tilt increment appeared to be the same as in the cases of zero and positive initial tilts. Thus, the independence of the tilt increment of the initial tilt is experimentally demonstrated.

The experimental setup allowed tilt measurements by varying the number of channels by means of appropriate tuning of VOAs. It is experimentally shown that, keeping constant the frequency separation between the first and the last channel (by which the tilt is defined), the dependence of the tilt $p_{max} - p_{min}$ (in dB) on the total power P_t of all channels (in W) is close to linear and does not depend on the number of channels. The measurements were performed for 40, 20, 10, and 2 channels.

The tilt value was also measured in the DWDM signal, produced by multiplexing the signals from different types of transponders. It was found that for a fixed spectral bandwidth and constant total power of the DWDM signal, the SRS-induced tilt does not depend on the number of channels (40, 20, 10, 5) and on the type of the source of radiation, propagating through the channel (we studied the noise source, 2.5G, and 40G transponders). The linear dependence of the tilt (in dB) on the total power (in W) is experimentally confirmed for DWDM signals with the spectral bandwidth varying from 0.3 to 4 THz.

Thus, the performed experimental studies confirm the high precision of Eqn (4). Deviations from Eqn (4) were experimentally observed only in tilt measurements with the signal having a strongly nonuniform spectrum. Such a signal was formed by three channels with the wavelengths 1561.42, 1549.32, and 1529.55 nm. The total power in the channels was kept constant (20 dBm). The powers in the extreme channels were equal; the power difference between the central channel and the extreme ones was varied.

The dependence of the tilt on the nonuniformity of the spectrum (the difference of power in the channels) is presented in Fig. 5. The obtained result may be explained by the fact that the real spectrum differs from the linear approximation: the ratio of the gain to the frequency detuning is a function of detuning, and this ratio is greater for frequency difference between the central channel and an extreme one than between the extreme channels.

Nevertheless, as follows from the previous Sections, the linear approximation of the gain spectrum is applicable for the analysis of the spectrum tilt in the majority of cases, practically important for DWDM communication systems.

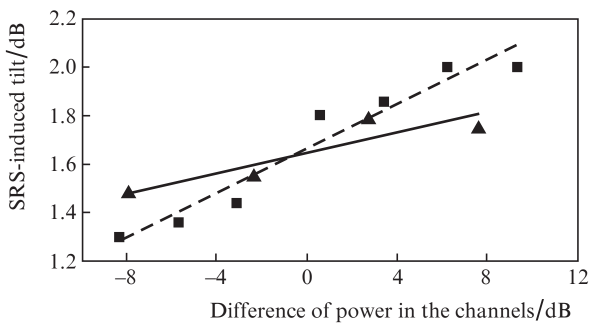

Figure 5. Dependence of the SRS-induced tilt for the 100 km-long segment of SMF fibre on the nonuniformity of the three-channel spectrum (difference between the power in the central channel and one of the extreme ones) at constant total input power 20 dBm for a noise source (solid line) and for three channels of the 2.5G transponder (dashed line).

24. Conclusions

In the present work the characteristics of the nonlinear SRS-induced tilt of the power spectrum of a multichannel DWDM signal in single-mode fibreoptic communication lines were studied. The coefficient of SRS-induced tilt in SMF and DCF fibres was measured.

It is demonstrated that the increment of tilt is independent of the initial tilt of the spectrum, the total tilt increment in a multispan communication line being proportional to the number of spans, the spectral bandwidth, and the total power.

It is shown that at a fixed spectral bandwidth and total power of the DWDM signal the SRS-induced tilt of the spectrum does not depend on the number of channels and the type of the source of radiation propagating through the channel.

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