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Optical Gain Stabilization of a Distributed Fiber Raman Amplifier

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The system of optical stabilization (Gain Clamping, GC) for gain of distributed SRS optical amplifier with forward pumping (Forward Distributed Raman Amplifier Unit, F-DRAU) was experimentally studied. For optical stabilization, spectrally selective, within one channel, optical feedback is created in the form of a linear resonator with Faraday mirrors. When the gain is unsaturated and exceeds the losses in the feedback circuit, generation occurs, ensuring stabilization of the gain at a level that exactly compensates the losses in the feedback circuit. The effect on the gain of individual channels of changes in the RAU pump power and the input power to the line was studied. It has been shown that optical stabilization makes it possible to reduce gain variations when changing the pump laser power and the total input power of the multichannel signal. In particular, it is shown that when using the proposed feedback method, changes in gain caused by fluctuations in input power by 8 dB were reduced from 1.9 dB to 0.2 dB. An algorithm for auto-tuning the pump power is proposed. This algorithm makes it possible to reduce the skew of the gain spectrum in a Raman amplifier with feedback and reduce energy consumption.

Keywords: Fiber Optics, Fiber Optic Amplifiers, Raman Amplifer Unit, Gain Clamping.

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Introduction

The need in communication network capacity of all levels is due to the creation of new data processing centers and extension of operating centers, traffic increasing in mobile networks 5G/6G, virtualization of network applications, and development of cloud services [1]. The increasing needs in speed of information transmission can be satisfied only by combination of multilevel modulation formats, the most state-of-art network equipment for data exchange [2,3] and technology of dense wavelength division multiplexing (DWDM) [4,5]. In DWDM-systems information is transmitted via many densely spaced spectral channels with various wavelengths, which are combined (multiplexed) and transmitted via same optical fiber. At the receiving side the spectral channels are separated spatially (demultiplexed) and enter the optical receivers [6,7].

DWDM technology is widely used in state-of-art long distance communication systems to increase the throughput capacity of the optical fibers. The optical amplifiers are used to increase operation distance of the optical systems. Erbium Doped Fiber Amplifers (EDFAs) are the most widely used in communication DWDM-lines and networks. However, with increasing use of the multilevel modulation formats with large spectral efficiency there is need in use of definite distributed amplifiers based on stimulated Raman scattering (SRS) (Raman Amplifier Units, RAU which ensure achievement of larger signal/noise ratio then the Erbium Doped Fiber Amplifiers do [8,9].

There are two types of RAUs — localized (discrete, lumped) (in-line Lumped Raman Amplifier Unit, LRAU, RAU) and distributed (Distributed Raman Amplifier Unit, DRAU). The localized RAUs are made by additional cartridges with fiber installation in fiber optic communication lines (FOCLs) to compensate dispersion (dispersion compensating fiber, DCF) or with highly nonlinear fiber (HNLF). In the distributed RAU the pumping is introduced into the same fiber, where the signal is distributed, thus ensuring distributed gain along the line length. Due to low effective area of the core and higher nonlinearity factor of HNLF and DCF the localized RAU require lower pumping power than the distributed RAUs to achieve the required gain level of the input signal. Anyway the localized RAUs are inferior to EDFA in terms of the noise and energy characteristics, and are less in demand in telecommunication [10–14].

During FOCL operation number of operating DWDM-channels can vary as result of planned connection or

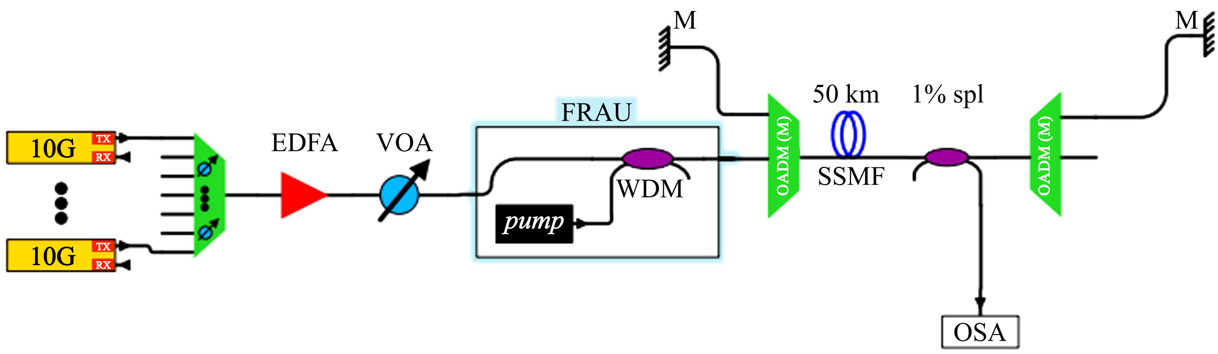

Figure 1. Diagram of the experimental setup. 10G TX — DWDM-transmitters; MUX — multiplexer; EDFA — Lumped Erbium Doped Fiber Amplifier; VOA — Variable Optical Attenuator; FRAU — pumping unit of RAU comprising pump laser (*pump*) with device of forward (signal co-directional) input of pump radiation into fiber line; M — Faraday mirrors; SSMF 50 km — standard singlemode fiber, 50 km; 1% spl — optic splitter 1/99%; OSA — optic spectrum analyzer; OADM (M/D) — add/drop multiplexer/demultiplexer; WDM — spectral selective splitter.

disconnection of channels, or due to failure in line. When amplifiers operate in saturation mode the change in channels number results in gain change accompanied by unwanted transients (power fluctuations) [15]. Besides, gain nonuniformity goes down, it is calculated for the fixed input power. So, gain clamping should be used to control these dynamic variations of gain [16,17]. Several ways to minimize transients in EDFA are known, for example, all-optical stabilization (gain clamping (GC)) [18,19] and electrical look-ahead regulation [20–22]. GC of EDFA gain is executed by a resonant cavity creation at one of work frequencies of amplifier and generation achievement in such resonant cavity which ensures gain clamping. (all-optical gain clamping (GC).)

Application possibility and perspectiveness of GC to stabilize RAUs were studied in less extent. Papers [23–29] demonstrated possibility of GC of localized (lumped) RAUs. In lumped RAUs the feedback is provided using ring [23–29] or, linear resonant cavities created by Bragg gratings [30].

In distributed RAUs GC with ring resonant cavities can not be practically implemented due to large losses in passive part of the resonant cavity. We know only one paper [31], where GC is implemented in the distributed RAUs using the linear resonant cavity formed by two fiber Bragg gratings (FBG). In present paper we demonstrated the principle possibility of GC of distributed RAUs, but detailed studies of its features, such as gain spectra distortion by generation channel and limits of applicability in actual FOCLs are absent.

Herein we suggest and study new optical system for stabilization of distributed RAU, based on feedback provided in spectral selective linear resonant cavity with Faraday mirrors. We show that GC reduces spectrum nonuniformity of signals gained by RAU. We suggested algorithm of pumping power self-tuning to minimize gain spectrum distortion by the generation channel, and reduce amplifier power consumption.

1. Experimental setup

The experimental setup diagram to study the gain clamping of the distributed RAU being part of the laboratory model of multichannel DWDM communication line is shown in Fig. 1. The laboratory DWDM communication system comprises 6 transmitters connected by spectral multiplexer (MUX), Erbium Doped Fiber Amplifier (EDFA), Variable Optical Attenuator (VOA), RAU pumping unit (*pump*) with forward (signal co-directional) input of pump radiation into fiber line, Add–Drop Multiplexer (OADM (M)), fiber line 50 km long (SSMF 50 km), Add–Drop Demultiplexer (OADM (D)). Radiation of the pumping unit *pump* converts the fiber line (SSMF 50 km) into the distributed RAU.

The linear resonant cavity is formed for the gain clamping using the Faraday mirrors M (power loss during reflection 0.2 dB), ensuring power reflection in wide spectral band, add–drop multiplexer and demultiplexer (OADM (M) and OADM (D), power losses 1 dB), and fiber line 50 km long (SSMF 50 km). Use of the wideband mirror ensures the possibility to select the generation wavelength using OADM. At gain of distributed RAU based on fiber line (SSMF 50 km) that exceeds the resonant cavity losses there is generation and resonance frequency set by the add–drop multiplexers (OADM (M)/OADM (D)). In generation mode the laser gain is equal to losses in the resonant cavity. When external radiation is applied to the active laser element at the generating wavelength the output power changes, and gain remains the same upon generation preservation. So, it is possible to use laser generation to ensure permanent gain of RAU within the entire work spectrum: decrease in total power of input optical signal is compensated by laser power increasing and vice versa.

The setup is assembled based on DWDM-platform „Volga“ manufactured by T8 Company. As radiation sources the transponder transmitters were used, their radiation wavelength was set to spectral channels 21, 28, 32, 37, 46, 51, 60 of normaliized by International Telecommunication Union (ITU) frequency grid [32] with wavelengths of 1560.61, 1554.94, 1551.72, 1547.72, 1540.56, 1536.61, 1529.55 nm. Signals of transponder transmitters TP are combined by the multiplexer MUX, where the attenuators tuning in each multiplexer channel ensures uniform spectrum of signal channels (standard deviation of channel power is maximum 0.03 dB). The multichannel DWDM-signal from MUX output after gain in EDFA and power tuning by the Variable Optical Attenuator VOA (EXFO LTB8) using OADM (M) is delivered into the line (SSMF 50 km). By means of spectral selective splitter (WDM) 4 RAU pump lasers (*pump*) emitting at wavelengths 1424.6, 1436.0, 1455.7, 1466.0 nm are connected to the line. Raman gain of signal occurs in coil of 50 km optical fiber SSMF. Linear resonant cavity creating the spectral selective feedback at wavelength of 1561.42 nm (20 channel) is formed by a pair of add/drop multiplexers (Optical Add-Drop Multiplexer, OADM) with Faraday mirrors installed upstream and downstream the fiber optic line (SSMF 50 km). The emission spectrum at output of the fiber optic line (SSMF 50 km) comprising multichannel DWDM-signal and radiation of stabilizing laser was measured using the Optical Spectrum Analyzer (OSA) Anritsu MS9740A connected via 1% coupler.

2. Results and discussion

2.1. RAU gain vs. pump laser power

According to definition, the differential gains of spectral channels are equal to difference between channel power at switched on RAU and switched off RAU, they are expressed in dB. For differential gains we use symbol $G_{\text{on-off}}$. Fig. 2 shows gain vs. pump radiation power P_{pump} at GC switched on (GC-on) and switched off (GC-off).

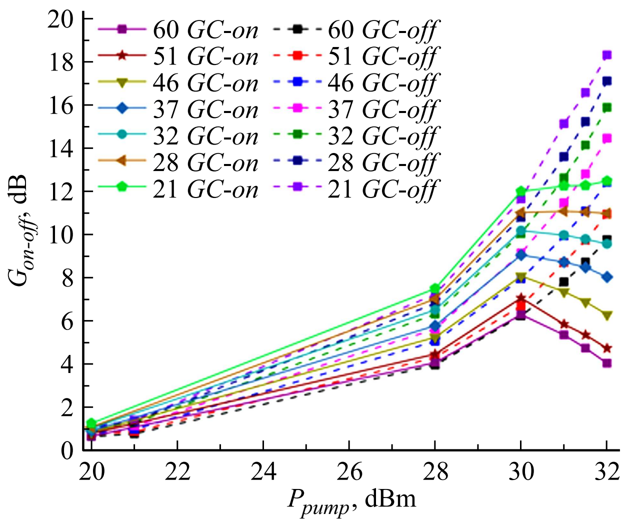

Figure 2. Gain ($G_{\text{on-off}}$) of signal channels vs. pump laser power P_{pump} at GC switched on (GC-on) and switched off (GC-off).

At RAU pump power ensuring exceedance of the threshold gain the generation is started at wavelength beyond the work band of the signal channels (channel 20, wavelength 1561.42 nm). As a result gain at generation frequency of the laser is stabilized at the threshold value determined by the losses in the resonant cavity. This ensures gain control using the variable Optical Attenuator. Graphs in Fig. 2 show that GC limits gain if the pump laser power increases. Radiation at the generation wavelength participates in SRS-processes, its power effect the signal gain, thus resulting in obvious dependence of gain of short wavelength channels on the pump power. This process complicates RAU GC as compared to the similar ways of stabilization EDFA [33–36]. At that, the closer the signal channel is to the generation channel, the better it is stabilized as per pump power. For channels that are more remote from the generation channel the effect of their power re-distribution to the generation channel is more pronounced.

2.2. RAU gain vs. input power

Dependence of RAU gain of each channel G_i on total input power was studied by several channels switching off and by power monitoring of the rest channels. Changes in total power under this experiment were 3 to 8 dB. Table 1 shows gain when all 6 channels are on, and gain changes relatively to these values ΔG_i when 3 and 5 channels are off. Values are provided for diagrams with gain clamping switched on/off , the switched off channels are marked with „×“. The pump power is set to 27 dBm.

The Table 1 shows that if GC is switched on the gains of all channels decrease on average by 2.9 dB, this is due to attenuation of RAU-pumping during radiation gain of the stabilizing laser, which power was 5.8 dBm. GC ensures significant decreasing of gain change, generated oscillation of output power are: 1.9 to 0.2 dB at input power decreasing by 8 dB. So, GC ensures gain stabilization of individual channels at input power changes.

2.3. Method reducing variations of spectrum distortion of RAU with gain clamping

Fig. 3 shows power spectra of channels after passing 50 km SSMF (see OSA location in Fig. 1) with RAU switched on in GC mode.

When GC is off RAU introduces significant spectrum distortion of input channel — 2.3 dB for six channels and 2.7 dB for three channels. As Fig. 3 shows that at permanent pump power of the Raman Amplifier Unit GC decreases spectrum distortion to 2 dB for six channels, and 2.3 dB for three channels.

The algorithm of RAU gain clamping as per generation power was suggested to reduce distortion of power spectrum of signal channels by the generation channel. The modified diagram of the experiment is presented in Fig. 4.

Table 1. Gains when channels are switched off

GC-off						
Switching	G_{60}, dB	G_{51}, dB	G_{46}, dB	G_{37}, dB	G_{32}, dB	G_{25}, dB
6 channels	13.8	15.1	15.5	15.8	15.8	16.1
	ΔG_{60}, dB	ΔG_{51}, dB	ΔG_{46}, dB	ΔG_{37}, dB	ΔG_{32}, dB	ΔG_{25}, dB
3 channels	0.8	×	×	1.2	×	1.2
1 channel	×	×	×	1.9	×	×
GC-on						
	G_{60}, dB	G_{51}, dB	G_{46}, dB	G_{37}, dB	G_{32}, dB	G_{25}, dB
6 channels	11.3	12.4	12.3	12.6	12.7	13.3
	ΔG_{60}, dB	ΔG_{51}, dB	ΔG_{46}, dB	ΔG_{37}, dB	ΔG_{32}, dB	ΔG_{25}, dB
3 channels	−0.1	×	×	0.4	×	0.2
1 channel	×	×	×	0.2	×	×

In the initial diagram the Power Meter (PM) was added, 1% of power in the generation channel near the first Faraday mirror is applied to this meter via the optical splitter.

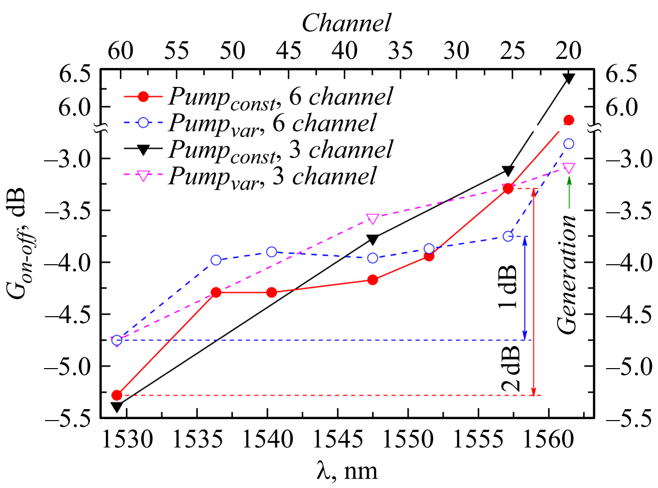

Figure 3. Power spectrum of signal channels with switched on RAU: $Pump_{\text{const}}$ — permanent pump power 27 dBm, $Pump_{\text{var}}$ — pump power self-tuning. Spectra are shown at 6 and 3 switched on signal channels (channels), 20th generation channel is marked (Generation).

Using this value the power self-tuning is performed in the generation channel near the threshold value −3 dBm, on average this by 1 dB exceeds the level of the signal channels. In mode of permanent pump power $P_{pump} = 27$ dBm, power in generation channel was 5.8 and 6.4 dBm at switched on 6 and 3 channels, respectively.

In Fig. 3 the power spectra in the pump power self-tuning mode are marked as $Pump_{\text{var}}$. It is shown that in this mode the nonuniformity of spectra decreases to 1 dB for 6 channels and 1.5 dB for 3 channels.

Dependence of RAU gain of each channel G_i on input power was studied similarly to mode of permanent pump power by switching off several channels and power monitoring of rest channels (Table 2). Table additionally contains values of power in the generation channel P_{gen} and pump power obtained in the self-tuning mode.

Table shows that gain changes due to input power variations are close to values obtained in mode of permanent pump power. In case of channels 37 and 25 we observe the ΔG exceedance of values obtained in mode of permanent pump power by 0.1 and 0.3 dB respectively. We associate this exceedance with rise of short wavelength portion of spectrum as result of power decreasing of the generation channel, this is clearly visible in Fig. 3.

Table 2. Gains at switched off channels in pump power self-tuning mode

Switching	G_{60}, dB	G_{51}, dB	G_{46}, dB	G_{37}, dB	G_{32}, dB	G_{25}, dB	P_{gen}, dBm	P_{pump}, dBm
6 channels	11.8	12.7	12.7	12.8	12.8	12.8	−2.9	26
	ΔG_{60}, dB	ΔG_{51}, dB	ΔG_{46}, dB	ΔG_{37}, dB	ΔG_{32}, dB	ΔG_{25}, dB	P_{gen}, dBm	P_{pump}, dBm
3 channels	0	×	×	0.4	×	0.5	−3.1	25.9
1 channel	×	×	×	0.3	×	×	−2.9	25.7

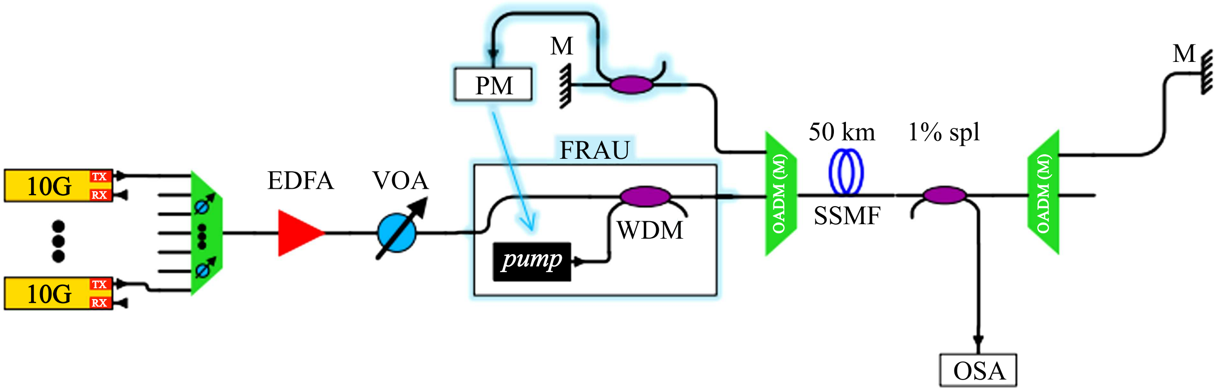

Figure 4. Diagram of experimental setup with possibility of RAU gain stabilization as per generation power. 10G TX — transponder channels; MUX — multiplexer; EDFA — Lumped Erbium Doped Fiber Amplifier; VOA — Variable Optical Attenuator; FRAU — Raman Amplifier Unit of forward pumping; M — Faraday mirror; SSMF 50 km — Standard Singlemode Fiber, 50 km; 1% spl — optical splitter 1/99%; OSA — Optic Spectrum Analyzer; OADM (M/D) — Add/Drop Multiplexer/Demultiplexer; WDM — spectral selective splitter; *pump* — pump lasers; PM — Power Meter.

So, the suggested mode of pump power self-tuning keeps advantages of pure gain clamping, such as response time and simple optical circuit. At that this reduces gain spectrum distortion by the generation channel, and also is the most energy saving as compared to classic Gain Clamping due to decrease in RAU pump power.

Conclusion

The original optical system of distributed RAU stabilization is suggested, the system is based on generation of induced radiation in the linear resonant cavity with Faraday mirrors. It is shown that GC reduces gain variations upon change in power of the pump lasers. Radiation at the generation wavelength participates in SRS-processes, its power effect the signal gain, thus resulting in obvious dependence of gain of short wavelength channels on the pump power. The shown GC decreases gain changes from 1.9 dB if GC is off to 0.2 dB with GC on. We show that GC reduces spectrum nonuniformity of signals gained by RAU. Also the algorithm of pump power self-tuning is suggested to achieve permanent generation power of the stabilizing laser. This algorithm decreases gain spectrum distortion by the generation channel, and makes GC more energy saving.

Conflict of interest

The authors declare that they have no conflict of interest.

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