Forward Pumped Distributed Raman Amplification in C and L bands Using Incoherent First-Order and Coherent Second-Order Pumps

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Abstract *We demonstrate forward-pumped distributed Raman amplification in C and L bands using semiconductor wideband incoherent optical sources as first-order pumps including newly developed incoherent optical sources for L band amplification. We confirm flat on-off gain and low relative intensity noise of transmitted signals. ©2023 The Author(s)*

Introduction

On forward-pumped Raman amplification, wideband incoherent optical sources used as pump sources suppress relative intensity noise (RIN) transfer from pump sources to optical signals[1,2]. Semiconductor wideband incoherent optical sources bring forward-pumped Raman amplifications close to practical use[1,3]. Hereafter, we refer to the semiconductor incoherent optical sources as iPUMPs and Fabry-Perot laser diodes with fibre Bragg gratings as coherent pumps (cPumps).

Forward-pumped Raman amplifications using iPUMPs improve quality of transmitted optical signals so that optical signal transmission capacity and/or length increases[1,4,5].

Bi-directional distributed Raman amplification (DRA) in entire C-band using iPUMPs as forward and cPumps as backward pumps shows better amplification characteristics than those of optical signals amplified by an erbium doped fibre amplifier (EDFA)[6]. In the DRA, iPUMPs with centre wavelength of 1425 nm and of 1466 nm are used to amplify entire C-band.

In this paper, we develop iPUMPs with centre wavelength of 1495 nm. Combination of iPUMPs with centre wavelength of 1425 nm, 1466 nm, and 1495 nm enables to amplify whole C and L bands by forward-pumped DRA. We measure amplification characteristics in whole C and L bands.

Characteristics of iPUMP for L-band amplification

iPUMPs consist of a seed semiconductor optical amplifier (SOA), a booster SOA, an isolator between the two SOAs, and an isolator at output of the booster SOA. These devices are placed in a standard 14-pin butterfly package.

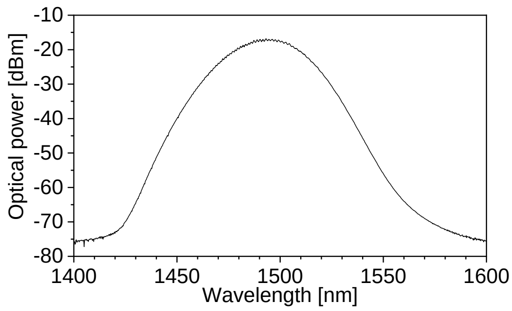

Fig. 1: Optical spectrum of a developed iPUMP with centre wavelength of 1495 nm

Since Ref.6 shows forward pumped DRA for whole C-band using iPUMPs with centre wavelength of 1425 nm and 1466 nm and with 3 dB bandwidth of 28 nm and 29 nm, respectively, iPUMPs with longer centre wavelength were necessary to amplify whole C and L band so that we developed iPUMPs with centre wavelength of 1495 nm.

Figure 1 shows output spectrum of the developed iPUMP. Measured centre wavelength is 1495 nm and 3 dB bandwidth is 30 nm. Figure

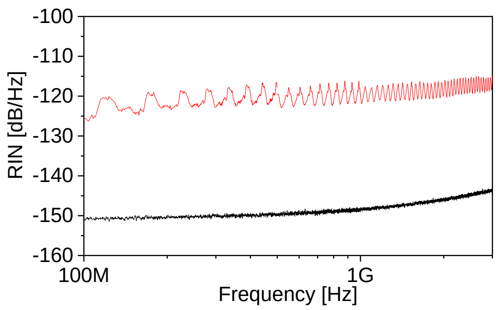

Fig. 2: RIN spectra of the developed iPUMP (black line) and of typical cPump (red line).

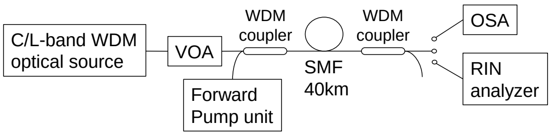

Fig. 3: Experimental setup.

2 shows typical RIN spectrum of the developed iPUMP. The RIN spectrum of the iPUMP is significantly lower than that of a typical cPump.

Experimental setup for C/L band forward pumped DRA

Figure 3 shows an experimental setup for forward pumped DRA. Forward pump unit consists of five cPumps and three iPUMPs. We used the three iPUMPs as first-order and the five cPumps as second-order forward pumps. The pumps were coupled using WDM couplers and polarization beam combiners. Depolarizers using polarization maintaining fibres were applied.

A C/L band wavelength division multiplexing (WDM) optical source consists of 24 optical signals in C-band, and 23 optical signals in L-band. Variable optical attenuator (VOA) controls input power of the WDM optical source to a transmission fibre. The WDM coupler after the VOA combines the WDM optical signal and the Raman pumps. A transmission fibre is G.652.D compliant standard single mode fibre (SMF) with length of 40 km. The WDM coupler after the SMF removes residual Raman pumps. Amplified WDM signal by forward-pumped Raman amplification is measured by an optical spectrum analyser (OSA) and RIN analyser.

Amplification characteristics

Figure 4 shows optical spectra of the WDM signal at the output of the VOA and of the forward pump unit at the input of the SMF. Input power of the WDM signal is 0 dBm/ch. Pump powers of cPumps and iPUMPs at the input of the SMF were adjusted to have flat on-off gain spectrum so that optimized pump power was obtained as shown in Tab.1.

Figure 5 shows optical spectrum at output of the SMF. Optical powers in longer wavelength among c-Pumps and among iPUMPs are higher than those of shorter wavelength because of inter-pump Raman amplification.

Figure 6 shows input WDM power dependence of on-off gain spectra. Averaged on-off gain was 7.5 dB so that the SMF loss is mostly compensated. Gain variation of the on-off gain for 0 dBm/ch WDM signal input is as small as 0.7 dB. Simulated on-off gain for input power of 0 dBm/ch shows good agreement with the measured one especially in longer wavelength region. The simulation was done based on pump wavelength

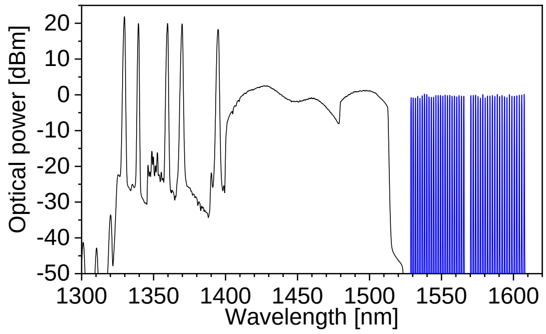

Fig. 4: Optical spectrum of the input WDM signal at the output end of the VOA (blue line) and the input pumps at the input of the SMF (black line).

Tab. 1: Pump powers at input of the SMF

	unit	cPump				
Wavelength	nm	1328	1338	1358	1368	1393
Power	mW	189	99	140	158	158

	unit	iPUMP		
Wavelength	nm	1425	1466	1495
Power	mW	89	38	75

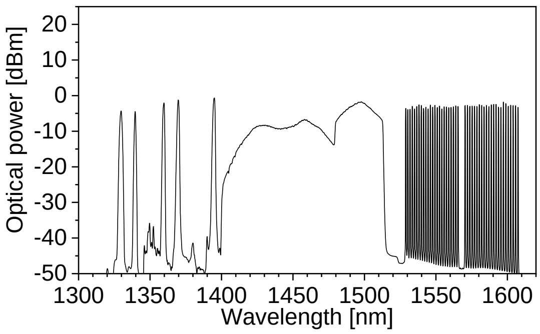

Fig. 5: Optical spectrum of output of the 40 km-long SMF.

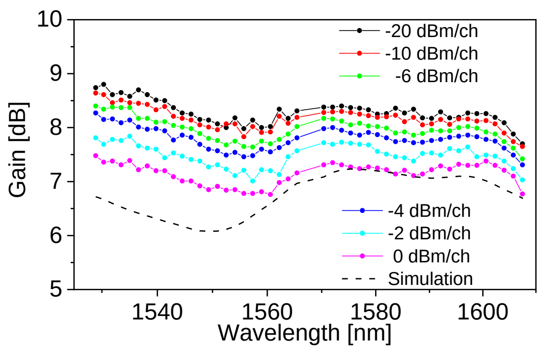

Fig. 6: Input power dependence of on-off gain spectra. Simulated one for input power of 0 dBm/ch is broken line.

and power and characteristics of the SMF.

Figure 7 shows input signal power dependence of the on-off gain for the optical signal with wavelength of 1546.11 nm as a typical C-band signal and 1588.72 nm as a typical L-band signal. Small signal gain exceeds 8 dB. The on-off gain decreases with increase of input signal power. At input signal power of 0 dBm/ch,

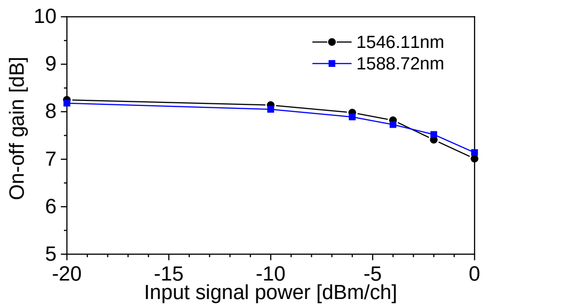

Fig. 7: Input signal power dependence of on-off gain for 1546.11 nm signal (black circles) and 1588.72 nm signal (blue squares).

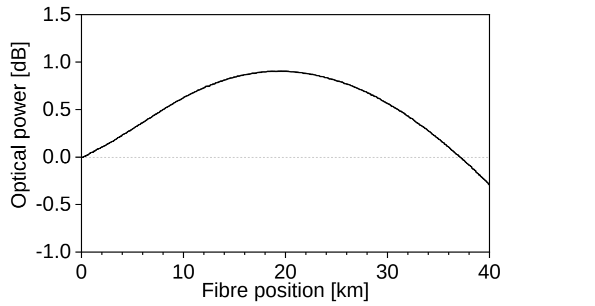

Fig. 8: Signal power evolution for 1550 nm OTDR signal.

gains decrease by about 1 dB because of pump depletion indicating slight gain saturation.

Figure 8 shows measured signal power evolution at around 1550 nm. The signal power evolution is measured by substituting an optical time domain reflectometer (OTDR) for the WDM optical source. Since optical power at 40 km is almost the same with optical power at input end, fibre loss was almost compensated. Maximum gain appears at around18.7 km with gain of 0.9 dB. The peak gain is about 1 dB smaller than that in Ref.6 where only iPUMPs are applied for the forward pumped DRA as first order pumps. Employment of c-Pumps as second order pumps results in the lower peak gain.

Output signal from the OTDR is so low that the forward-pumped DRA operates in small signal gain region. Peak gain could be decreased with increase of input signal power.

Characteristics of transmitted signal

We measured RIN spectra of the transmitted signal under forward-pumped DRA. As reference RIN spectra, we measured RIN spectra of transmitted signal amplified by an EDFA after the SMF transmission without using the forward-pumped DRA.

Figure 9 and 10 show RIN spectra for optical signal with wavelength of 1546.11 nm as a typical C-band signal and 1588.72 nm as a typical L-band signal, respectively. The RIN spectra of the signals amplified by the forward-pumped DRA are smaller than those amplified by an EDFA.

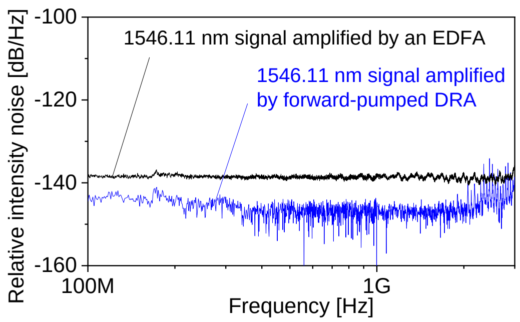

Fig. 9: RIN spectrum for 1546.11 nm signal amplified by the forward pumped DRA (blue line) and an EDFA (black line).

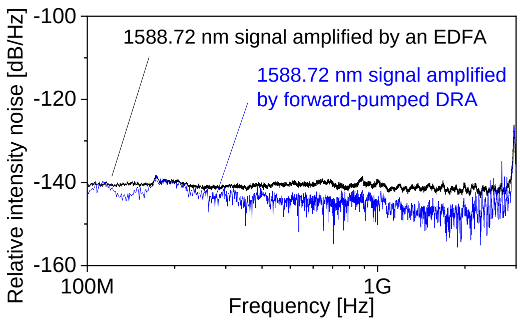

Fig. 10: RIN spectrum for 1588.72 nm signal amplified by the forward pumped DRA (blue line) and an EDFA (black line).

Summary

We developed the iPUMPs with centre wavelength of 1495 nm for L-band DRA. We demonstrated the forward-pumped DRA for C and L bands with 40 km-long SMF using the three iPUMPs in 1400 nm region as first-order and the five cPumps in 1300 nm region as second order pumps.

We measured flat on-off gain in C and L bands with averaged gain of 7.5 dB and with gain variation of 0.7 dB. RIN spectra of the transmitted signals were lower than those of the signals amplified by an EDFA. Maximum gain appears at around 18.7 km with gain of 0.9 dB.

An 80-km long SMF transmission of optical signals in whole C and L bands by a combination of forward-pumped DRA using iPUMPs as first-order and cPumps as second-order pumps and backward-pumped DRA would be feasible.

Acknowledgements

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