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Low noise, intelligent cladding-pumped L-band EDFA

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Abstract

We present results on a low-cost cladding-pumped L-band amplifier based on side pumping (GTWave) fibre technology and pumped by a single 980-nm multimode diode. We show that simultaneous noise reduction and transient suppression can be achieved by using gain clamping by a seed signal (λ = 1564 nm). In the gain clamping regime, the amplifier exhibits 30 dB gain over 1570-1605 nm spectral band with noise figure below 7 dB. The noise figure can be further reduced to below 5 dB by utilising a low power single-mode pump at 980 nm. The EDFA is relatively insensitive to input signal variations with power excursions below 0.15 dB for a 10 dB channel add/drop.

Index Terms

Erbium-doped fiber amplifiers, gain clamping, optical fiber communication, wavelength division multiplexed systems

Introduction

The L-band transmission window (1570-1605 nm) has been of special interest for optical transmission system designers not only because it offers a direct route to expand the transmission capacity of the current optical systems operating in C-band (1525-1565 nm) but also because it gives more flexibility in system design. L-band erbium-doped fibre amplifiers (EDFA) take advantage of the tail of the erbium gain band, which is far away from the emission peak (~1530 nm). Because of the small erbium emission cross-sections in the L-band, the fibre must be quite long to achieve sufficient gain. The efficiency of L-band EDFAs is lower than that of C-band EDFAs because of the low cross-section, and also because a large amount of amplified spontaneous emission (ASE) is generated in the C-band. Furthermore, background losses can be significant in long EDFAs. L-band EDFAs are thus power-hungry and core-pumped devices require multiple high-power pump diodes at 980 nm and 1480 nm [1].

Multiple stage configurations, ASE end-reflectors [2], [3] and C-band seeds [4], [5] and pumps [6] have been used to improve the efficiency by suppressing the C-band emission, but the fundamental problem with the small emission cross-sections remain. Therefore, even with some form of suppression of the C-band emission, core-pumped L-band EDFAs require multiple high-power pump diodes. From this standpoint cladding-pumped L-band EDFAs offer a cost-effective alternative to traditional core-pumped devices. In particular cladding-pumping offers greater flexibility in erbium-doped fibre design and brings down the cost of the pump diodes, since high-power, but low-cost multimode pump diodes can then be used.

In addition to low-cost, an L-band EDFA for WDM systems should be able to offer flat gain, low noise figure and insensitivity to sudden changes of input power during channel add/drop operation. In this paper, we present results on a low-cost cladding-pumped L-band amplifier based on GTWave fibre technology and pumped by a single 980-nm multimode diode. We also show that low noise figure (≤5 dB) and small power excursions (<0.15 dB) during 10 dB channel add/drop can be achieved by a gain-clamping technique.

Measurement results and discussion

The experimental set-up and the configuration of the cladding-pumped L-band EDFA are shown in Fig. 1. The EDFA is based on GTWave fibre technology where two or more optical fibres share the same external coating [7]. In this case the GTWave fibre assembly has two fibres: one core-less, undoped silica fibre used as a pump fibre (outer diameter 60 μm) and one Er-doped fibre with a cut-off wavelength of 1500 nm, absorption of 14 dB/m at 980 nm for light propagating in the core, and a core diameter of 10 μm (outer diameter 60 μm). The outer diameters of the fibres and the core diameter of the doped fibre were chosen to maximize the pump confinement within the doped core. The GTWave fibre is 50 m long and is pumped by a pigtailed broad-area laser diode spliced to the pump fibre. The amplifier has a single-stage, without any gain-flattening filter. Note that with GTWave fibre technology no pump WDM is needed either. The pump diode operates at 980 nm and is capable of delivering up to 1.5 W of optical power in a 50-μm, 0.22 NA core all-glass multimode fibre pigtail. A variable-power control beam at 1564 nm is injected into the core together with the signal for gain-clamping. The pump, signal, and gain clamping beams are all propagating in the same direction through the amplifier. This configuration minimizes the noise figure. However, we also tried other configurations. With 700 mW of absorbed pump power the GTWave EDFA is delivering 21 dBm of saturated output power. Note that the amplifier is pumped by a single pump diode and the output power of the amplifier can easily be doubled with bi-directional pumping. Alternatively, the output power can be scaled up by having multiple pump fibres in the GTWave assembly pumped by several high-power broad-area pump diodes.

The single channel gain and noise figure of the EDFA with co- and counter-propagating pump and signal is shown in Fig. 2. As expected the gain and noise figure are higher for the counter-propagating configuration. The small-signal gain is higher than 30 dB over the 1570-1605 nm band. The gain flatness is ± 2 dB for the co-pumping configuration with signal input powers in the range from –20 dBm to 0 dBm. Especially for shorter wavelengths, the noise figure is relatively high due to the build-up of short wavelength gain and high ASE-power, leading to a compressed gain in the front section of the amplifier. With input power from –11 dBm to –2 dBm the noise figure is below 7 dB across the whole gain band from 1570 nm to 1607 nm (Fig. 4).

In the experiments, we used a gain-clamping DFB-laser at 1564 nm co-propagating with the signal. During channel add/drop the power from the clamping laser changes to compensate the increase or decrease in input power, i.e., the clamping laser is turned up as channels are dropped and turned down as channels are added. The improvement of the noise figure and gain flatness is shown in Fig. 3. The input signal power in both gain measurements is –20 dBm. The clamping power at 1564 nm is –3 dBm. The gain is compressed by 3 dB and the resulting gain flatness is ±1 dB over the 1570-1605 nm band. The noise figure is improved by more than 1 dB due to the reduction of the short wavelength gain and hence the build-up of the backward propagating ASE power. The noise figure can be improved even more by further increasing the inversion in the front section of the fibre, for example, by pumping the EDFA with a single-mode 980 nm pump diode with an optical power of 50–100 mW.

As shown in Fig. 4, with 100 mW of 980 nm core-pumping power, the noise figure is ≤5 dB across the whole gain bandwidth for input powers ranging from –25 dBm to –5 dBm. In the figure, the worst-case noise figure (at 1570 nm) is presented. With low input powers, (-25 dBm to –15 dBm), C-band injection is required to reduce the NF below 7 dB. A combination of an auxiliary signal at 1564 nm and 980-nm core-pumping with moderate pump power (100 mW) results in the lowest noise figure (≤5 dB). We have also measured the gain and noise figure with different gain clamping wavelengths (1530, 1540, 1550 and 1560 nm). However, the noise figure improvement decreases as the wavelength is shortened because the clamping signal begins to act as a pump for L-band signals.

As shown earlier, the transient response of an L-band amplifier is slower than C-band EDFAs [8]. This is explained by the higher intrinsic saturation power in the L-band (due to lower absorption and emission cross-sections) that leads to lower relaxation rates via stimulated emission [9]. In addition, the typically larger core size of cladding-pumped fibres further increases the intrinsic saturation power and thus the transient response time.

The transient behaviour of the surviving channel in the GTWave L-band EDFA was measured using two sources at 1590 nm and 1595 nm. The input power of the surviving channel (1595 nm) for 3 dB drop is –9 dBm and for 10 dB drop –16 dBm. The dropping and adding of the channels is simulated by a 1590-nm signal modulated by an acousto-optic modulator at 10 Hz. The total input power to the amplifier is –6 dBm before the drop. The transient power excursions of the surviving channel are monitored by a fast oscilloscope and are shown in Fig. 5. The worst-case power excursion for 10 dB add is 0.15 dB, thus verifying the sufficient speed of our transient suppression circuit. The overall settling time of the amplifier is below 1 ms. The small offset in the transient response can be decreased by applying a slight offset to the transient suppression circuit.

The system performance of the amplifier under channel addition/dropping conditions is analysed in BER-measurements. In the measurements a 10 Gb/s modulated signal passes through the amplifier. An external Mach-Zehnder modulator imposes an NRZ pseudo-random bit sequence with 2^{31}-1 word length on the optical carrier. Results from the system measurements are shown in Fig. 6. The input power of the surviving channel is –16 dBm (1595 nm) and the total input power to the EDFA is –6 dBm. Back-to-back curve (solid curve) corresponds to a situation where there is no EDFA present in the measurement set-up. The dashed curve in the figure represents a case when the surviving channel and the unmodulated DFB laser simulating the added/dropped channels (1590 nm) are launched into the EDFA. The power penalty of 0.4 dB is mainly caused by the high noise figure of the EDFA. As the DFB laser is modulated with the AOM to simulate the 10 dB channel add/drop and the gain suppression circuit (and the clamping laser) is turned on, the penalty is reduced to 0.2 dB. The reduction of the penalty is attributed to the decrease of noise figure resulting from the C-band injection to the EDFA.

Conclusions

We have presented results on a single-stage, low-cost cladding-pumped L-band amplifier based on GTWave fibre technology pumped by a single 980-nm multimode diode. We have shown that by using gain clamping, simultaneous reduction of the noise figure and suppression of unwanted transient effects under the channel add/drop operation can be achieved. The cladding pumped amplifier exhibited 30 dB gain over a 1570-1605 nm gain band with noise figure below 7 dB and power excursions below 0.15 dB for 10 dB variations of input power. The noise figure can be further reduced below 5 dB by increasing the inversion in the front section of the EDFA by low power (<100 mW) 980 nm core-pumping. Power penalty free operation of the amplifier for 10 dB variations of input power was verified in BER measurements.

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Figure captions

Fig. 1. Schematic lay-out and the measurement set-up of the gain-clamped L-band EDFA based on GTWave technology.

Fig. 2. Gain and noise figure of the cladding-pumped EDFA with different pumping directions. Input signal power is –20 dBm and 0 dBm. Absorbed pump power is 700 mW.

Fig. 3 Gain and noise figure of the cladding-pumped EDFA as the gain clamping laser is turned on/off. Input signal power is –20 dBm and the clamping power is –3 dBm.

Fig. 4. The worst-case gain and noise figure (at 1570 nm) of a cladding-pumped L-band amplifier as a function of input power.

Fig. 5. Transient power excursions of the surviving channel as the optical channels are added and dropped (drop/add ratio 10 dB). The total input power to the amplifier is –6 dBm and the power of the surviving channel is –16 dBm.

Fig. 6. BER curves for a –16 dBm/ch signal as the input power to the EDFA is constant (no clamping laser) and as the input power is varied by 10 dB (clamping laser on). Total input power to the EDFA is –6 dBm.

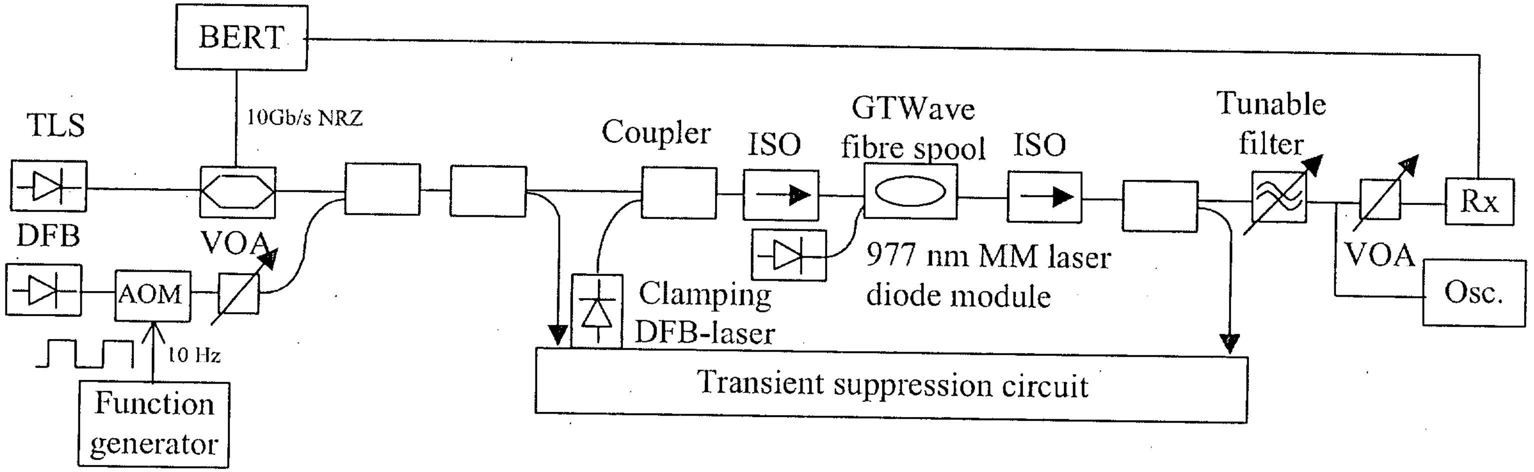
BERT
10Gb/s NRZ
TLS
DFB
VOA
AOM
10 Hz
Function generator
Coupler
ISO
GTWave fibre spool
ISO
Tunable filter
VOA
Rx
Osc.
977 nm MM laser diode module
Clamping DFB-laser
Transient suppression circuit

Figure 1

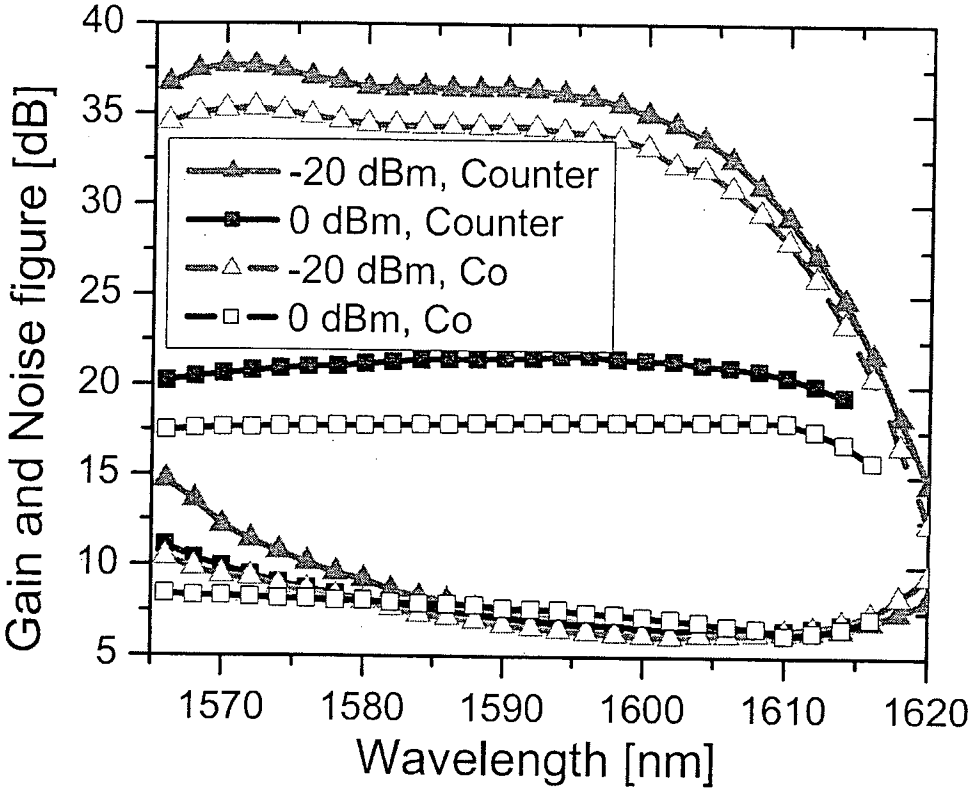
40
35
30
25
20
15
10
5
1570
1580
1590
1600
1610
1620
Gain and Noise figure [dB]
Wavelength [nm]
-20 dBm, Counter
0 dBm, Counter
-20 dBm, Co
0 dBm, Co

Figure 2.

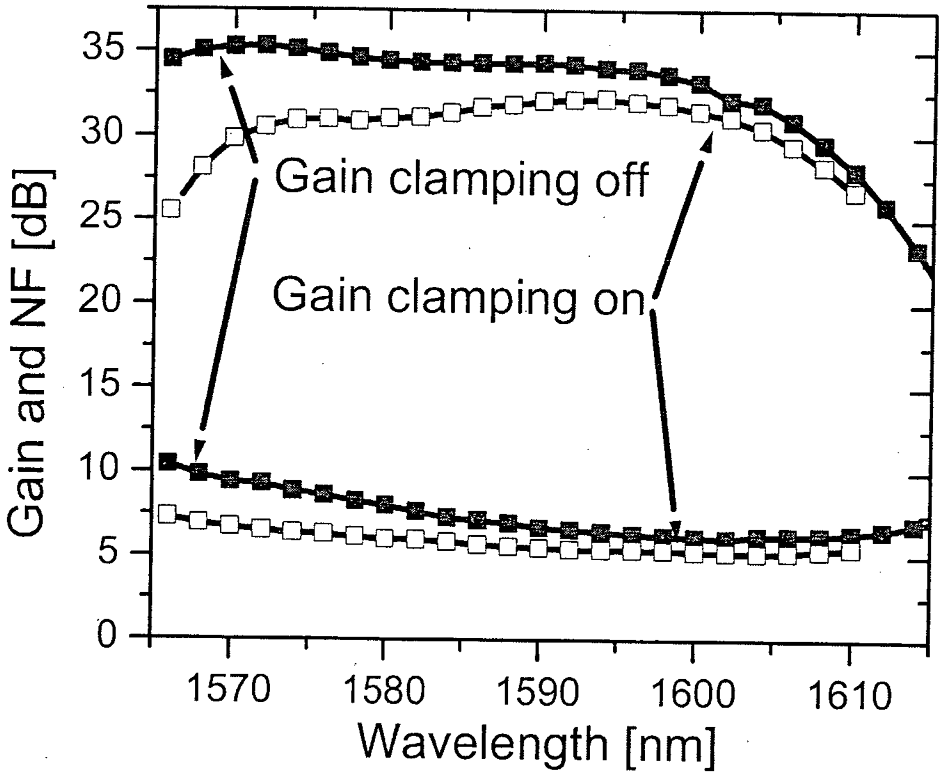
35
30
25
20
15
10
5
0
Gain and NF [dB]
1570
1580
1590
1600
1610
Wavelength [nm]
Gain clamping off
Gain clamping on

Figure 3.

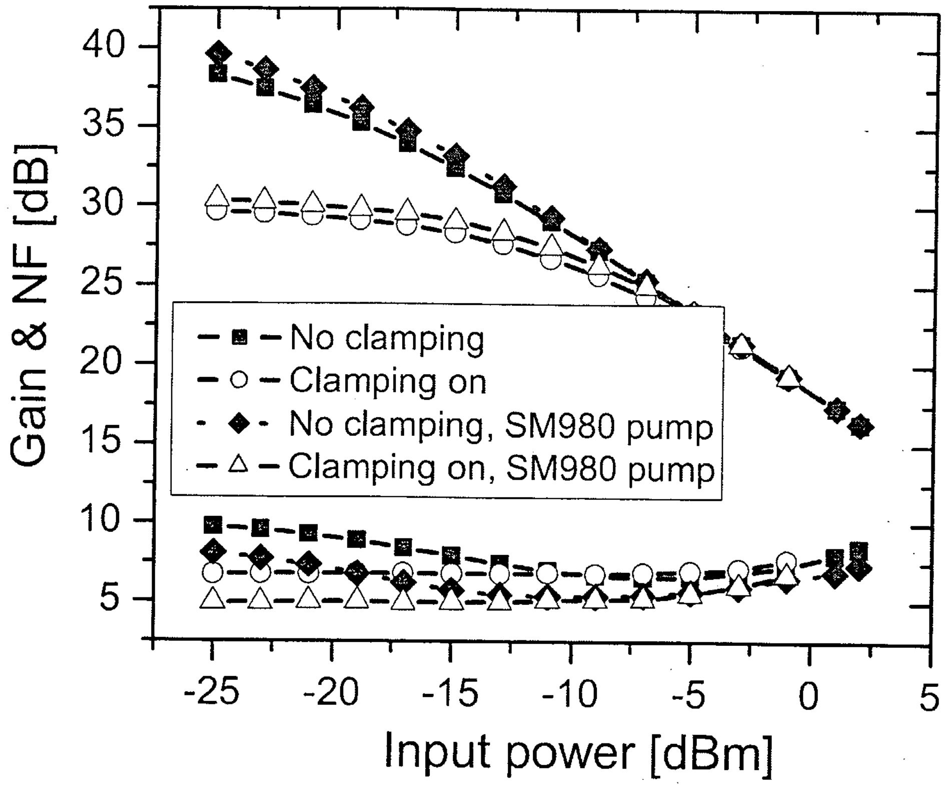
Gain & NF [dB]
40
35
30
25
20
15
10
5
Input power [dBm]
-25
-20
-15
-10
-5
0
5
– ■ – No clamping
– ○ – Clamping on
- ◆ - No clamping, SM980 pump
– △ – Clamping on, SM980 pump

Figure 4.

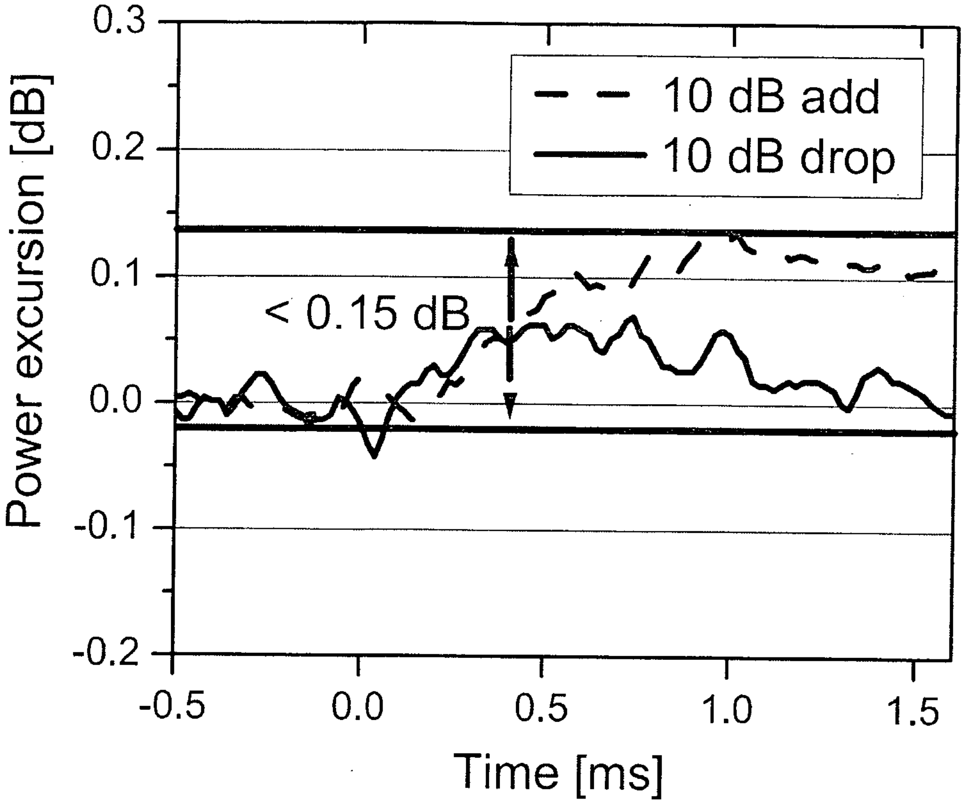
0.3
0.2
0.1
0.0
-0.1
-0.2
Power excursion [dB]
-0.5
0.0
0.5
1.0
1.5
Time [ms]
10 dB add
10 dB drop
< 0.15 dB

Figure 5

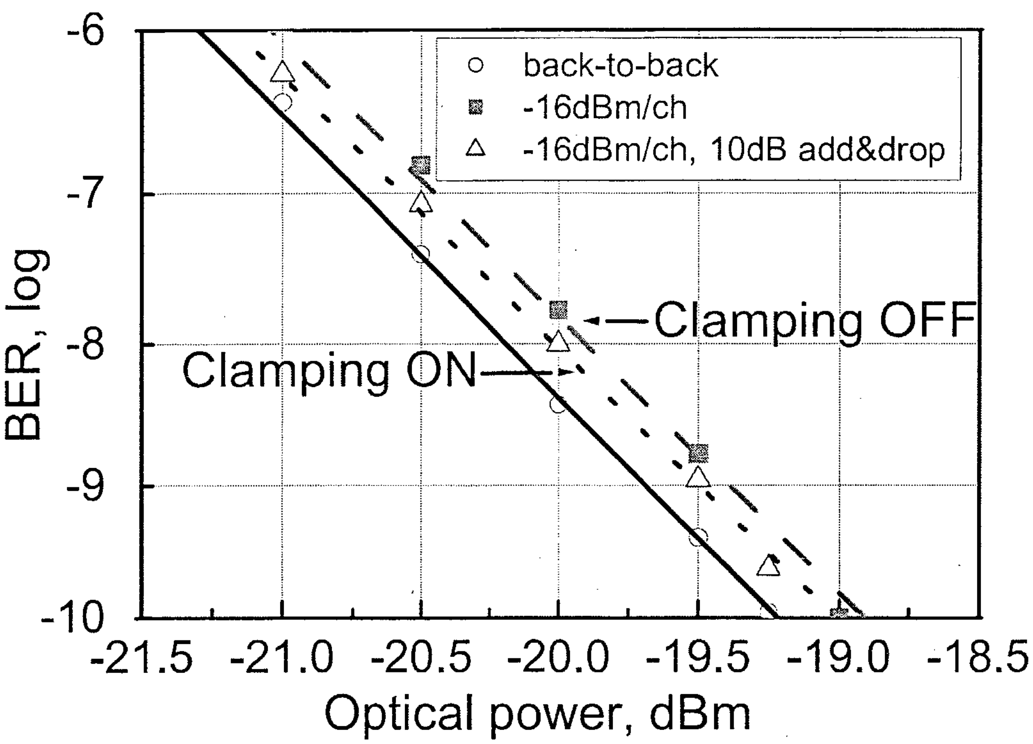
-6
-7
-8
-9
-10
BER, log
-21.5
-21.0
-20.5
-20.0
-19.5
-19.0
-18.5
Optical power, dBm
○ back-to-back
■ -16dBm/ch
△ -16dBm/ch, 10dB add&drop
Clamping OFF
Clamping ON

Figure 6