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Performance Optimization of Broadband Communication System using Hybrid Parametric Amplifier

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Abstract

We describe a model of Raman-parametric hybrid amplifier and present its simulation results for flat gain amplification in Dense Wavelength Division multiplexed (DWDM) terabits capacity system. In the proposed configuration single pump FOPA is cascaded after Raman to form a hybrid with each implemented in separate length of fiber. This allows for maximum optimization of gain achieved using Raman as well as parametric processes separately. We also focus on the signal degradation due to non-linear crosstalk, in particular due to generated idlers within the operational bandwidth. It has been demonstrated that a maximum gain of 35.5 dB for 96 X 40 Gbps, 25 GHz system is attainable up to 300 km of transmission distance while maintaining OSNR > 18 dB using proposed hybrid. No gain compensation or gain optimization technique has been used. Flat gain in narrowband DWDM systems is achievable through proper optimization of pump wavelengths and their powers.

Keywords: DWDM, parametric amplifier, Flat Gain, Raman, hybrid amplifier

INTRODUCTION

Multi-channel DWDM are currently ruling the optical transmission scenario due to their high capacity, fast multi-user data transmission [1, 2]. But as the channel spacing shrinks and data rate increases, passive losses coupled with optical nonlinearities has made optical amplifiers necessary for success of long distance DWDM systems. Fiber Optical parametric amplifiers (FOPA) with their capabilities to provide large gain, broad band amplification [3], [4] and low noise Fig. [5]make promising amplifiers for such systems [4], [6]. Raman amplifiers is another class of optical amplifiers capable of providing wide, tunable bandwidths in excess of 100 nm with low gain ripple (< 1.5 dB) in WDM applications in [7-8]. Raman amplifiers as well as FOPAs [9, 10-15] can be tuned across any band, thus making hybrid of optical parametric and Raman hybrid suitable as tunable broad band amplifiers. Raman-FOPA hybrid has been significantly attractive over traditional FOPAs due to their flexibility and extended gain bandwidths [16-21].Golovchenko et al [19] examined the phase mismatch parametric gain and have demonstrated that the gain depends strongly on the real part of the complex Raman susceptibility. In conventional RA-FOPAs, most energy from the Raman amplifier is trapped in the parametric pump at the output end of the amplifier. So, Wang et al [20] in his work has focused on conventional RA-FOPA configuration using Raman pumping assisted parametric gain in piece of HNLF. He suggested proposed a hybrid fiber Raman/parametric amplifier (HFRPA) constructed by cascading a FOPA after the RA-FOPA demonstrating gain enhancement of 34 dB compared to a conventional RA-FOPA. Ummy et al [21] demonstrated the extended flat gain of about 15 dB of with gain ripple of 5 dB, using combined Raman and parametric interaction in HNLF. But Peiris et al [22] demonstrated hybrid Raman-Optical Parametric amplifier (HROPA) in Tandem configuration for extended bandwidth, with gain more than 20 dB and extended gain bandwidth of 170 nm and gain ripple of less than 4 dB.

In [23] improved performance with RA-FOPA for WDM system has been achieved with net gain of 20 dB and gain ripple of 1.9 dB for 10, 100 GHz spaced DFB lasers. Use of tunable NRZ signals showed reduced susceptibility to saturation of gain in Raman-FOPA hybrid [24]. Kaur et al [25] have demonstrated Raman-FOPA cascade for 96 X100 Gbps system with 25 GHz spacing to give gain of 14 dB over L-band. Hybrid amplifier of Raman cascaded with two section FOPA has been demonstrated to achieve wide bandwidth of 220 nm by Kaur et al [18]. In our work Raman-FOPA cascade instead of conventional Raman-assisted because of following reasons:

1. It allows pumps of Raman and FOPA to be independently tuned in complementary regions. Raman amplification requires longer interaction lengths while parametric amplifiers use short length HNLFs. The proposed system used 12 km of FRA while 200m HNLF is used in FOPA.
2. Raman Fiber can be utilized for amplification as well as

dispersion compensation allowing implementation of Raman amplifier in distributed or discrete configuration.

3. The amplified output of Raman amplifier serves as input to FOPA. This increased signal power at its input helps achieve better FWM efficiency responsible for parametric amplification.

In this paper we attempt to demonstrate the feasibility of long haul DWDM systems using the proposed Raman-FOPA cascade and achieve flat gain through optimization of pump wavelengths and their powers requiring no gain compensation technique. Results indicate increased ability of Raman-FOPA hybrid as tunable, broad band, and flat gain amplifier suitable for long distance DWDM systems. The results reported are best in terms of gain and gain flatness for Raman-FOPA hybrid in DWDM systems.

EXPERIMENTAL SETUP

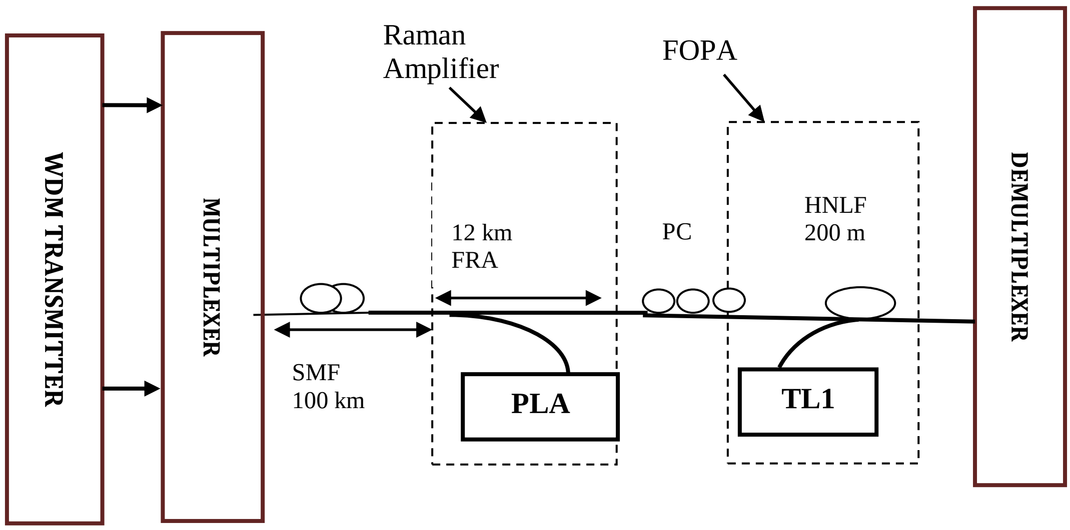

Figure 1: Schematic for Experimental set up. FRA-Fiber Raman Amplifier, PC- Polarization Controller, PLA-Pump laser Array, TL-tunable laser

The HNLF parameters used for FOPA are as specified in Table 1.

Table 1: Parameters Used For HNLF

Parameter	**Value**
HNLF dispersion slope	0.02 ps/nm^{2}km
HNLF coefficient	17.83 (Wkm)$^{-1}$
HNLF Length	200m
HNLF attenuation	0.8dB/km

Experimental set up comprises of a DWDM system with equally spaced 96 channels in L-band from 187 THz to 189.375 THz with RZ 40 Gbps modulated signal and channel spacing of 25 GHz has been simulated to analyze the performance of RAMAN-FOPA. Fig. 1 shows the experimental setup. In the given model, signal traverses 120 km of transmission fiber duly dispersion compensated using DCF.

The gain expected of RAMAN-FOPA hybrid is:

$$G_{Hybrid} = G_{Ram\ an} + G_{FOPA} \quad (1)$$

Where, G_{Hybid} gain of the proposed Raman-FOPA expressed in decibels.

For investigating the feasibility of proposed Raman-FOPA hybrid for a terabits capacity DWDM system in long haul communication a 96 channel, 25 GHz , RZ 40 Gbps system has been proposed. The aim of this evaluation of proposed hybrid is firstly to achieve flat gain without using any gain equalization/compensation technique. To evaluate the feasibility of proposed Raman-FOPA hybrid for long haul DWDM system by careful optimization of the number of pumps, their wavelengths and their powers to achieve flat gain while maintaining the minimum OSNR of 18 dB.

In first phase of our investigation the experimental set up of Fig. 1 uses Raman amplifier with 8 pumps from 1480 nm to 1540 nm. The wavelengths of Raman and parametric pumps are so tuned that they amplify complimentary sub-bands of bandwidth under consideration. Raman-FOPA cascade serves as inline amplifier in the proposed set up. The input signal after traversing transmission fiber of 120 km is first launched in to the Raman amplifier. 12 km of SMF has been used in Raman amplifier with back propagating pumps. Unlike Raman assisted FOPA using same piece of HNLF [20], separate SMF has been used in Raman amplifier. This helps achieve higher gain in proposed cascade as Raman amplification is based on longer interaction lengths whereas parametric amplification uses short length HNLF. Raman amplified signal are then coupled to Continuous wave (CW) laser source serving as pump for parametric amplification at 187.315 THz. In our model, the state of polarization of the input and pumps is assumed to be aligned, which may not always be true in practical systems.

RESULTS AND DISCUSSION

The proposed configuration uses 8 Raman pumps equally spaced from 1480 nm to 1540 nm with pump wavelengths and the respective pump powers as shown in Fig. 2a to provide gain in L-band from 1583 nm to 1603 nm. The 120 km fiber span has been dispersion compensated using 19.56 km of DCF with D= -90 ps/nm/km and S= 0.112ps/nm^2/km. Parametric pump is placed at 187.315 THz with 27 dBm power. Results in Fig. 2b show remarkable gain flatness with highest gain of 51.76 dB and minimum gain of 48.39 dB with a low gain ripple of 3.37 dB without any gain compensation technique.

This has been the highest gain achieved so far for L-band over longest transmission distance using Raman-FOPA hybrid amplifier. The achievement of high gain of 51.8 dB is attributed primarily due to use of high pump powers of the order of 650mW but at the cost of OSNR. Analyzing the OSNR achieved, Fig. 2b shows significant fall in OSNR at higher wavelengths.

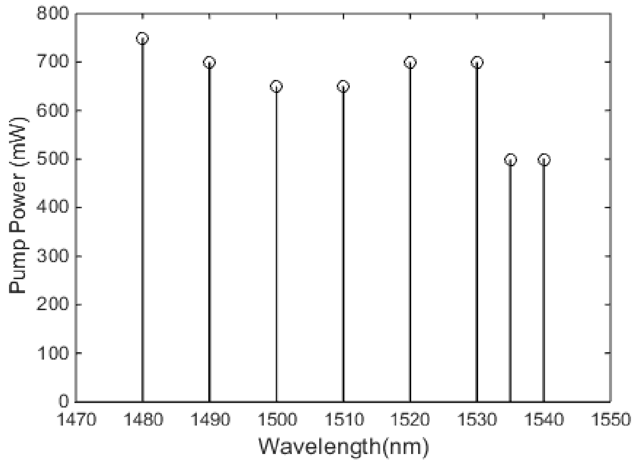

Figure 2a: Raman pump powers for un-optimized 96 channel DWDM system

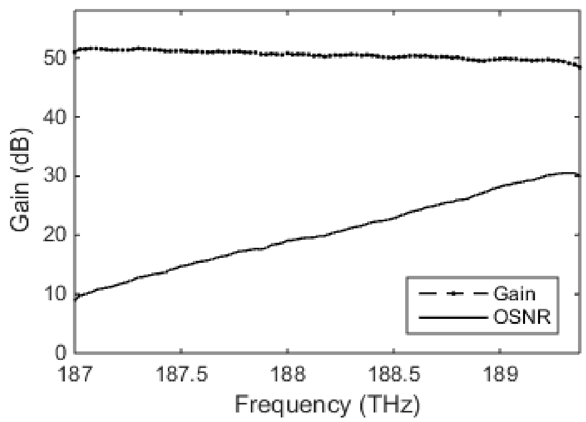

Figure 2b: Gain and OSNR variation of the un-optimized system

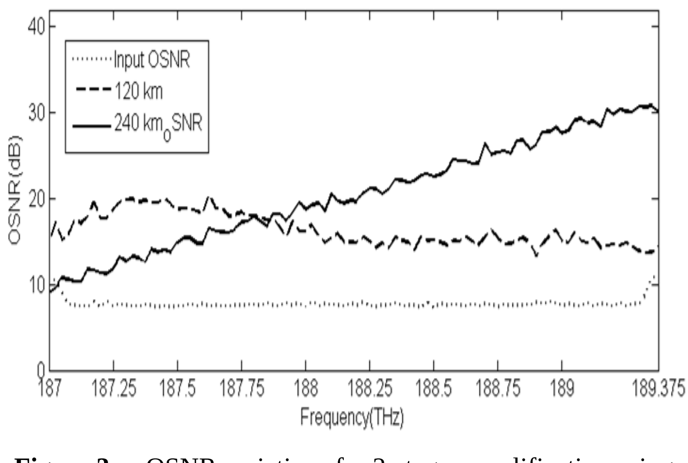

Figure 3a: OSNR variations for 2-stages amplification using un –optimized pump powers

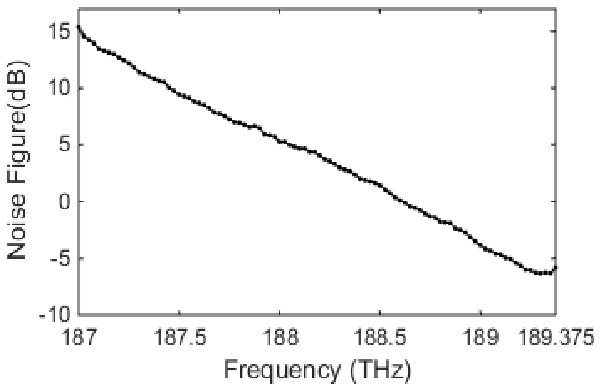

Figure 3b: Noise Fig. variations of the proposed hybrid using un –optimized pump powers

The minimum OSNR achieved is as low as 9 dB at the higher wavelength xtremes. In practical systems OSNR of less than 18 dB makes signal undetectable at the output So, even high gain of 51.8 dB with ripple of nearly 3 dB achieved with proposed Raman-FOPA hybrid makes it unattractive and insignificant for long haul, DWDM systems. The fall in OSNR may be attributed to the use of high pump powers leading to high noise in Raman amplifier dominant at higher wavelength contributed primarily by Double Rayleigh Scattering (DRS) and Amplified Spontaneous Noise (ASE) [26]. DRS is believed to limit the gain per stage when used over multiple stages in long haul communications. This is well observed from OSNR variation of two stage amplification OSNR profiles shown in Fig. 3a.In multi-pump configuration, the dominant source of noise is pump-pump interaction [27]. Since ASE manifests itself as beat signal [26] produced on interaction with co-propagating signal it is accounted for in idler signal generated due to FWM in proposed Raman-FOPA cascade.

The input OSNR as shown in Fig. 3a at 1mW input power has value of 7 dB at all channels except at band extremities. After traversing 120 km SMF transmitted signal are compensated by 19.56 km DCF and then amplified by inline Raman-FOPA hybrid amplifier. OSNR increases to maximum value of 19.98 dB and minimum value of 14.32 dB. But as the transmission propagates through next SMF span of 120 km DCF compensated fiber OSNR increases to maximum value of 30.8 dB at higher end of frequency band while minimum value of 8.95 dB occurs at 187 THz. Though the gain is uniform but OSNR is monotonously increasing as seen from solid curve in Fig. 3a.The non-uniformity in OSNR is due to presence of noise sources both at amplifiers as well as in the transmission channel. With high pump powers of more than 650 mW pump –pump interaction noise dominates. This is well supported by noise Fig. variations shown in Fig. 3b which shows a very high noise Fig. at higher wavelengths (near 187 THz) leading to poor OSNR at these wavelengths. Noise Fig. shown in Fig. 3b falls in line with noise Fig. expected of multi-stage Raman amplifier with gain increasing at longer wavelengths and noise Fig. falling with increased Raman gain [26].The fall in OSNR in spite of high values of gain is attributed to losses induced by multi-pump interactions at high pump powers between Raman pumps and interaction between Raman pumps and high power parametric pump.

Apart from noise sources in Raman amplifier, FOPA suffers crosstalk both from transmission fiber nonlinearities as well as non-linear effects of parametric amplifier itself. As the number of channels increase in WDM system the FOPA crosstalk dominates over transmission channel non-linear effects [13]. The dominant non-linear effects of FOPA are Four wave Mixing (FWM) and cross Gain modulation (XGM).These non-linear crosstalk is coupled with ASE and Raman scattering noise which coincides with bandwidth of parametric amplification. Though the parametric pump used in proposed model is not EDFA amplified ASE due to parametric pump is ignored but the amplified quantum noise [28] leads to idler signal variations at output thereby affecting the parametric gain. Parametric pump alone can provide high gain over wide bandwidth but with increase in number of channels single pump FOPA does not effectively amplify.

Wang et al [16] derived a theoretical model for RA-FOPA using multiple Raman pump assisted FOPAs. Flat gain over 40 nm bandwidth is demonstrated with gain enhancement of 15 dB over conventional FOPA. This makes Raman-FOPA cascade attractive for terabits multichannel systems. From the analysis of noise sources in Raman and parametric amplifiers above it may be established under given set of assumption for state of polarization, and absence of EDFA pumped source, use of multiple Raman pumps at high powers is the dominant cause of increased quantum and beat signal noise in the proposed set up.

In second phase of our investigations we attempt to optimize our system performance in terms of gain, gain flatness and OSNR. Performance optimization has been achieved with respect to optimal transmission fiber span length, number of Raman pumps and their powers, and parametric pump wavelength and power.The optimized system proposed uses Raman- FOPA cascade as inline amplifier after 100 km SMF transmission fiber. So the fiber span is reduced to 100 km dispersion compensated by 19.56 km of DCF. The number of Raman pumps have been reduced to 7 for 96 channels with power varying as shown in Fig. 5. In the optimized scenario Raman pump powers are of the order of 350 mW while the parametric pump is maintained at high power of 500 mW. The parametric pump is tuned at 189.315 THz that is in the low wavelength region while Raman pumps provide gain at longer wavelengths. The results achieved after the optimization of pump powers in Fig. 5a shows the peak gain of 35.5 dB reducing the maximum gain against the peak gain of 51.8 dB achieved in the un-optimized scenario. On the contrary, due to decreased number of pumps and their reduced power the minimum achievable OSNR of 18 dB has been achieved against low OSNR of 9 dB in the un-optimized system. Additionally, the OSNR variation between the maximum and minimum OSNR has reduced from 21.8 dB to 15.68 dB after use of optimized pump powers. The results for optimized configuration have been analyzed up to three fiber spans of 100 km, each dispersion compensated by 19.56 km of DCF. So, the OSNR above 18 dB have been achieved over 300 km of total fiber transmission against previous results analyzed after fiber transmission distance of 240 km only.

Results in Fig. 5a show maximum gain of 35.5 dB and minimum gain of 32.04 dB reducing the gain ripple to 3.46 dB. Though there is significant drop in maximum gain from 51.8 dB to 35.5 dB of nearly 16.3 dB but optimized pump powers outperforms as it achieves:

1. Minimum required OSNR of 18 dB and improvement in OSNR variation by 6.12 dB.
2. Increased transmission distance of up to 300 km
3. The gain ripple of 3.46 dB.
4. Improved BER

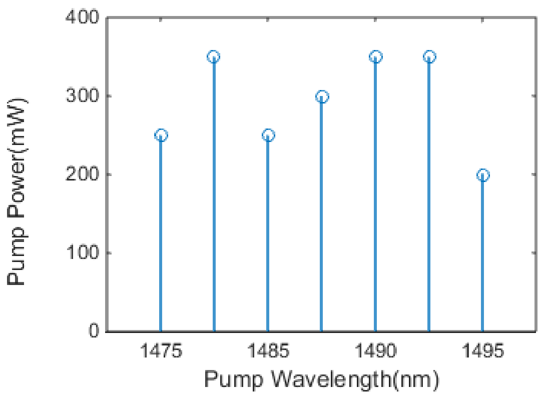

Figure 4: Optimized Raman pump wavelengths and their powers for proposed system

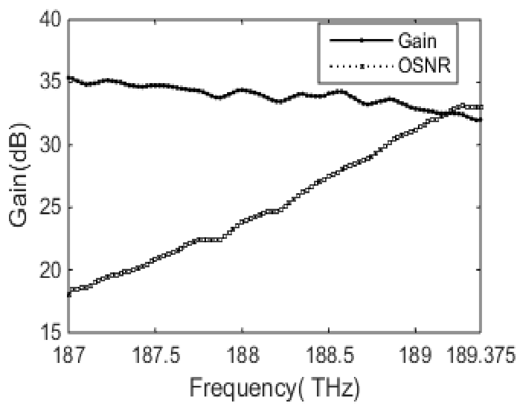

Figure 5a: Gain and OSNR Variations for optimized Raman pump powers over transmission distance of 300 km

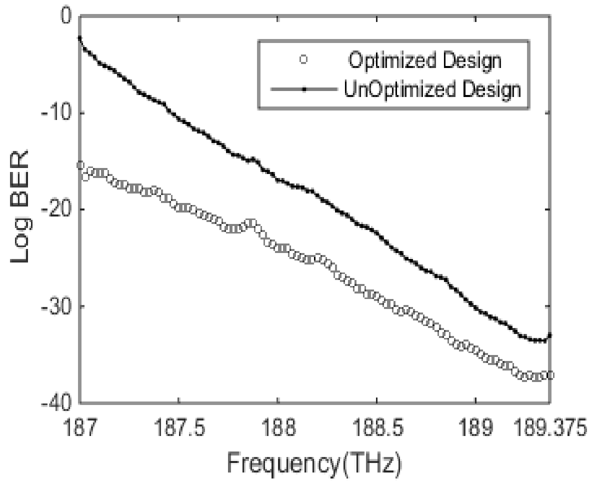

Figure 5b: Log BER comparison for Optimized and Un-optimized pump powers

This is the highest gain achieved for 40 Gbps multichannel system with narrow channel spacing of 25 GHz. Increased gain is achievable but at cost of reduced transmission distance. No gain equalization technique has been used in the proposed design yet flat gain with reasonably low ripple of 3.46 dB has been in L-band DWDM systems. The improvement in BER due to optimization is shown in Fig. 5b. It can be clearly seen for optimized pump powers minimum BER of 10^{-14} is achievable while in un-optimized design even though gain was significantly higher, BER has minimum value of 10^{-2}, which is far less than minimum acceptable BER of 10-^{9}.

So the proposed Raman-FOPA cascade as an inline amplifier for DWDM systems establishes its feasibility as inline amplifier in long haul DWDM systems with careful optimization of Raman and parametric pumps.

CONCLUSION

A novel Raman-FOPA cascade for L-band terabits capacity 96X40 Gbps DWDM has been proposed. The effect of Raman amplifier noise sources and parametric amplification crosstalk for multichannel DWDM has been studied. Results prove that Raman –FOPA hybrid can be tailored for any band in useful communication 1400-1650 nm band for flat gain without any compensation techniques. Raman- FOPA cascade gives the flexibility to tune Raman and FOPA gain in different sub-bands and hence achieve flat gain. For multichannel system, use of multiple pumps significantly adds to noise due to pump-pump interactions. So attempt has been made to optimize the number of pumps and their powers to provide distributed amplification over entire band. Single pump FOPA is then tuned with high power pump to boost the signal level in band of frequencies where Raman gain falls. High gain can be achieved using high power pumps but leads to significant increase in crosstalk significantly increases, making noise comparable with that of propagating signals. Single pump FOPA has been used with high pump power whereas or non-uniform Raman pumps with powers less than 350 mW have been used to keep pump-pump interaction noise minimum.

Distributed pumps with sufficient wavelength spacing have been used and Raman pumps are placed far from ZDWL as well pump wavelength of FOPA to minimize FOPA-Raman pump interaction crosstalk.

Additionally, unlike Raman-assisted parametric amplifiers which make use of same HNLF as FOPA, the proposed cascade uses separate SMF for Raman amplification as Raman gain is proportional to length of fiber. This helps in Raman gain enhancement. Short lengths of HNLF of 200m are used for parametric amplification. Another important finding is optimal fiber span. The optimal distance for near 100 channels Transmission system is 100 km. Increasing the fiber span beyond 100 km (compensated or uncompensated) reduces OSNR and signal strength drastically. This paper explores the feasibility of Raman-FOPA hybrid for terabits long haul DWDM transmission. So far no work has been reported to achieve average gain of more than 25 dB using Raman-FOPA hybrid after 200 km of fiber transmission at 40 Gbps. The proposed hybrid can be optimized with respect to polarization sensitivity and dispersion characteristics. Dispersion characteristics of fiber used for Raman amplification can be tailored to achieve dispersion compensation as well [16]. Use of advanced modulation formats [29, 30] at high data rates > 80 Gbps combined with wideband gain capabilities of parametric amplifiers [31] can add significant results to realizing flat gain amplifiers for high capacity multichannel systems in future.

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