Long Distance Signal Transmission in CATV Network Using Distributed Raman Amplification

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Abstract- **Distributed Raman amplification based long distance fiber optic transmission systems have been widely deployed for telecommunication applications. Several scattering effects and multiple reflections in a field-installed fibers posed stringent conditions for analog transmission for conventional CATV applications. However, recent advances in grating technology and the development of high-power diode pump lasers have revived interest in distributed Raman amplifiers. In this paper, we propose techniques to improve the performance of distributed Raman amplification based CATV long distance transmission**.

Index Terms- Analog Signal Transmission, CATV, Long Distance Transmission, Optical Amplification, Raman Amplification.

I. INTRODUCTION

The Distributed Raman Amplification (DRA) in long distance high capacity data communication has been proved to be an effective means of providing relatively flat gain over wide bandwidth [1-4], and is one of the key elements for future broad bandwidth high capacity WDM optical fiber links. For the delivery of Internet and other data services between long haul and access networks, transmission speed and distance in metropolitan area networks are increasing. In addition, cost competition for data services force the system integrators to consider advanced, high specification, components and amplification schemes at lower price to extend the non-amplified sections in metropolitan networks.

There are two types of amplifiers reported in the literature based on stimulated Raman scattering: discrete Raman amplifier and DRA. For long distance transmission of optical signals, DRA based systems has several advantages such as implementation simplicity, the transmission fiber could be used as the amplifying medium, flexibility since amplification can occur at any wavelength, potential broad bandwidth and gain flattening by combining different pump wavelengths, expansion into the S-band and low noise figures compared with EDFA. High power semiconductor lasers became commercially available at competitive price and Raman amplifiers have become a viable alternate to the EDFA.

Due to high Carrier-to-Noise Ratio (CNR) requirement, DRA for analog transmission in CATV network has not been studied extensively. To achieve high analog performance, the optical signal level throughout the transmission line must be kept as high as possible. We studied the possibilities and limitations of long distance analog CATV signal transmission, and in this paper, we propose techniques to improve the performance of signal transmission.

II. THEORETICAL BACKGROUND

As illustrated in the energy-level diagram in Fig.1, some pump photons give up their energy to create other photons of reduced energy at a lower frequency (inelastic scattering); the remaining energy is absorbed by silica molecules in the form of molecular vibrations(optical phonons), which end up in an excited vibrational level.

These vibrational levels determine the frequency shift and shape of the Raman gain curve. Due to amorphous nature of silica fibers the Raman gain curve fairly broad. For the case of standard single mode fiber (SMF), in terms of wavelength, a maximum gain occurs at Raman shift of 100nm. For example maximum gain occurs at a wavelength of around 1550nm when pump wavelength of 1450nm is used.
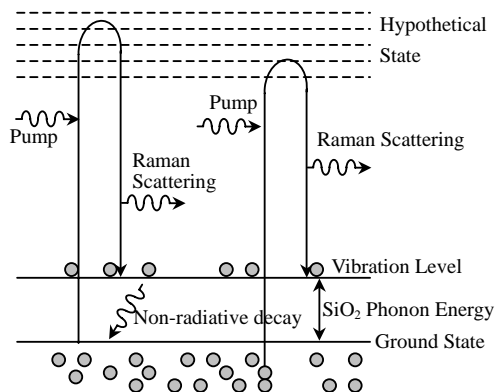

Fig.1. Energy levels participating in the SRS process.

Schematic configuration of a typical DRA system is shown in Fig.2. Both forward and backward pumping can be used. However, to avoid the intensity noise transfer from pump to signal, backward pumping scheme is often used. Variations of pump and signal powers along the transmission distance can be studied by solving the following coupled equations[1].
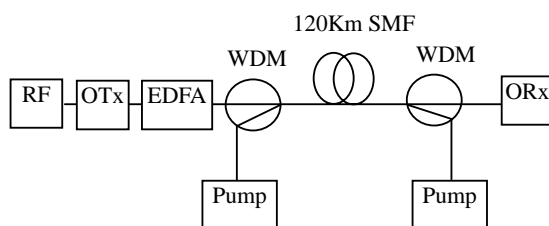

Fig.2. Schematic of typical long distance signal trans-mission link in a CATV network

When the transmission is assumed to be along the z-direction, the pump and signal variation takes the form,

$$\frac{dP_s(z)}{dz} = -\alpha_s P_s(z) + \left(\frac{g_R}{K\,A_{eff}}\right)P_p(z)P_s(z) \qquad (1)$$

$$\pm\frac{dP_p(z)}{dz} = \alpha_p P_p(z) + \left(\frac{\omega_p}{\omega_s}\right)\left(\frac{g_R}{K\,A_{eff}}\right)P_p(z)P_s(z) \qquad (2)$$

where, $P_p(z)$, $P_s(z)$ are the pump and signal power along the transmission direction respectively. $\alpha_p(\alpha_s)$, $\omega_p(\omega_s)$ are the transmission loss at pump(signal) wavelength and the frequency of pump(signal) beam respectively, g_R is the Raman gain coefficient, and A_{eff} is the fiber effective area of cross-section. K=1, if pump and signal polarizations are matched, and K=2 otherwise. $\pm$ indicate the backward and forward pumping respectively. The first and second terms of Eqn.(1) correspond to pump transmission loss and pump depletion respectively. The pump depletion can be neglected in the small-signal approximation. The effective area, A_{eff} is given by,

$$A_{eff} = \frac{\int\limits_{-a}^{a}\psi_p^2(r,\theta)\,r\,dr\,d\theta \int\limits_{-a}^{a}\psi_s^2(r,\theta)\,r\,dr\,d\theta}{\int\limits_{-a}^{a}\psi_p^2(r,\theta)\psi_s^2(r,\theta)\,r\,dr\,d\theta} \qquad (3)$$

where, ψ_p and ψ_s are the pump and signal field distributions respectively, a is the fiber core radius.

III. LONG DISTANCE CATV TRANSMISSION

We conducted experiments on long distance transmission of CATV signals. NTSC analog channels (8 channels in the VHF band) and digital channels (23 QAM channels in the super high band) are used for the experiment. The bandwidth of analog and digital channels is 6MHz and digital channel powers are –10dB from the analog channels. The modulation index for the analog and digital channels are 8%/Ch and 2.5%/Ch respectively, and the total modulation index is around 24%. The number of analog channels is kept small to improve the system performance. Seven un-modulated carriers and one actual CATV signal is used. TV monitor is used to evaluate the transmitted signal

quality. The signals are frequency multiplexed and transmitted using 1550nm externally modulated transmitter. The optical power launched at the input is kept small (13dBm) to account for larger transmission losses of the deployed fiber, and to reduce SBS effects.

Signals are transmitted over a distance of 120Km with a transmission loss of 0.215dB/Km and are converted back to RF signals using an optical receiver. Band pass filters and spectrum analyzer are used to measure the CNR performance. 300mW of pump power at 1450nm wavelength with built-in grating for better spectral characteristics is used for the measurements. With the received optical power of –9.5dBm, a CNR of 47dB and 38dB is obtained for the analog and digital channels respectively. This received power corresponds to a gain of 6.5dB. For digital signals, a CNR of 35dB is sufficient for error free transmission, and for analog signals, a CNR of more than 50dB is required. Increase of pump power, although the received optical power increases, will not improve the CNR performance for the following reasons.

CNR of the analog signal degrades continuously along the transmission line, and with the Raman amplification, total CNR of the system will be decided by the CNR at a distance of 30Km (effective length) from the pump. Therefore, increase of pump power will increase the power level at the receiver and the CNR will remain constant. This is the main reason why the DRA system has not been employed in the long distance CATV analog transmission. There are other factors that affect the transmission quality. Since the Raman amplification process is extremely fast compared to EDFA, any fluctuation of pump frequency can cause fluctuation of Raman gain and leads to fluctuation of signal power. Rayleigh scattering and multiple reflections in the fiber link can also increase the noise level [5].

IV. IMPROVEMENT OF SYSTEM PERFORMANCE

CNR requirement for digital CATV transmission

is not very critical. For the case of analog signals, the optical power at the receiver and along the transmission line must be kept high enough to achieve the required CNR. The following solutions are proposed to improve the system performance.
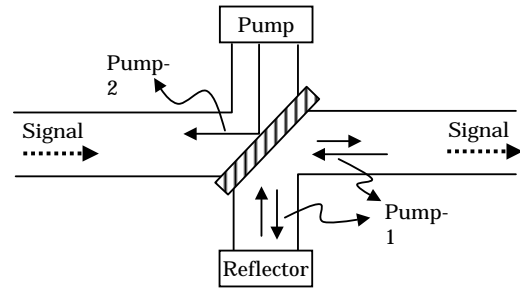

Fig.3. Pump beam reflector and second pump at a distance L_1 from the transmitter.

The first solution is to include a pump reflector at an optimum distance L_1 from the transmitter as shown in Fig.3. Wavelength selective filters and reflectors have been studied extensively and reported in the literature [3]. The details on the design and fabrication of these filters and reflectors are not considered and appropriate optical components are in the present study. Next, a second pump (Pump-2) is considered at the same distance L_1 as shown in the Fig.3. As described above the Pump-1 is reflected and simultaneously the Pump-2 is launched into the fiber, which counter propagates with the signal. Analytical solutions for Eqns.(1), (2) are derived as follows, where the solution is considered for the two regions on either side of the reflector position L_1.

For $z < L_1$

$$P_s(z) = P_s(0)\exp\left(-\alpha_s z + \left[\frac{g_R}{K\,A_{eff}}T_1\,P_{p1}e^{-\alpha_p L_1}(e^{\alpha_p z}-1)\frac{1}{\alpha_p}\right] + \left[\frac{g_R}{K\,A_{eff}}T_2 P_{p2}e^{-\alpha_p L_1}(e^{\alpha_p z}-1)\frac{1}{\alpha_p}\right]\right) \qquad (4)$$

For $z > L_1$

$$P_s(z) = P_s(0)\exp\left(-\alpha_s z + \right.$$

$$\left[\frac{g_R}{KA_{eff}} T_2\, P_{p2}(1-e^{-\alpha_p L_1})\frac{1}{\alpha_p}\right]+$$

$$\left[\frac{g_R}{KA_{eff}} T_1\, P_{p1}e^{-\alpha_p L}(e^{\alpha_p z}-1)\frac{1}{\alpha_p}\right]+ \quad (5)$$

$$\left[\frac{g_R}{KA_{eff}} P_{p1}e^{-\alpha_p L}(e^{\alpha_p z}-e^{\alpha_p L_1})\frac{1}{\alpha_p}\right]+$$

$$\left.\left[\frac{g_R}{KA_{eff}} R\, P_{p1}e^{-\alpha_p(L-L_1)}(1-e^{-\alpha_p(z-L_1)})\frac{1}{\alpha_p}\right]\right)$$

where, $P_s(0)$ is the input signal power. P_{p1} and P_{p2} are pump power, and T_1 and T_2 are transmissivity of of Pump-1 and 2 respectively, R is the reflectivity of Pump-1, and L is the total transmission length.

V.NUMERICAL EXAMPLES AND DISCUSSION

Gain coefficient, g_R is measured as follows[4]:

$$g_R(\lambda) = \left[\frac{KA_{eff}}{P_p(L)L_{eff}}\right]\ln\left[\frac{P_s^{PumpON}(L)}{P_s^{PumpOFF}(L)}\right] \quad (6)$$

$$L_{eff} = \frac{1-\exp(-\alpha_p L)}{\alpha_p} \quad (7)$$

With unpolarized beams ($K=1$), A_{eff} is calculated using Eqn.(3) to be $81.6 \times 10^{-12}\text{m}^2$. The measured transmission loss at signal and pump wavelengths are α_s =0.215dB/Km and α_p =0.27dB/Km. When P_p = 300mW and L = 120Km is used the gain coefficient and effective length are measured to be, g_R =6.22 x 10^{-14}m/W and L_{eff}=16.1Km respectively. The measured gain spectrum of the SMF and Dispersion Shifted Fiber (DSF) using a pump of 300 mW at 1450nm are shown in Fig.4. Maximum gain occurs around 1550nm, and the wavelength dependence is same for the two fibers. The gain bandwidth is more than 30nm. We considered only standard SMF, as they are most commonly used in the CATV network. As can be observed from Fig.4, the frequency dependence of Raman gain is same for both kinds of fibers,

and the gain peaks at a Stokes shift of about 13.2 THz. The gain bandwidth is about 6 THz if we define it as the FWHM of the dominant peak in Fig.4.

Raman gain coefficient, g_R as given by Eqn.(6) is related to the optical gain, which in turn depends on the cross-sectional area of the pump beam inside the fiber. Since A_{eff} can vary considerably for different types of fibers, the ratio g_R/A_{eff} can be considered to be a measure of the Raman gain efficiency [7]. We conducted experiments to measure the gain spectrum only with standard SMF and DSF. A dispersion compensation fiber (DCF) can be eight times more efficient than standard SMF because of its smaller core diameter. The wavelength dependence of gain spectrum with DCF is similar to that of standard SMF and DSF. However, DCF is not commonly used in the CATV network.
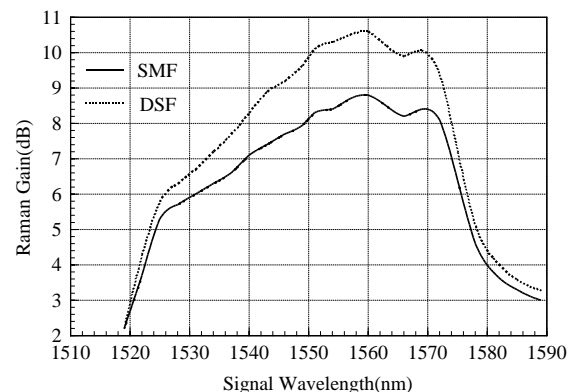

Fig.4 Raman gain spectrum for SMF and DSF

Fig.5 shows the calculated signal power variation in a conventional DRA system; with input signal power of 13dBm and different backward pumping powers. The calculated gain of 8.2dB is value close to the measured value.

As shown in the figure, the amplification started from a distance of around 80Km from the transmitter. This length is decided by L_{eff} . The overall CNR of the system is the same as the CNR level at this distance. Increase of pump power leads to more gain and higher optical power reaches the receiver. Another factor affects

the CNR is the lower optical power (around -4dBm) at the receiver. We can understand that, increase of both received optical power and signal level before the distance of 80Km is necessary to improve the CNR performance.
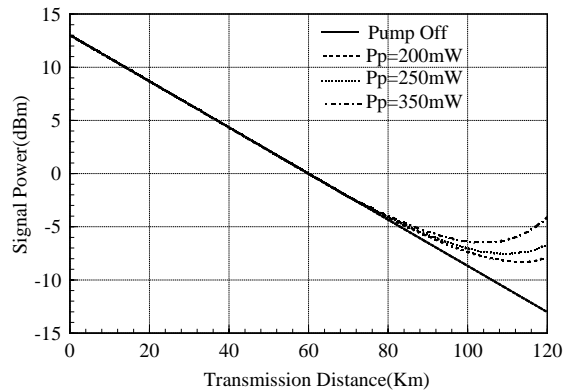

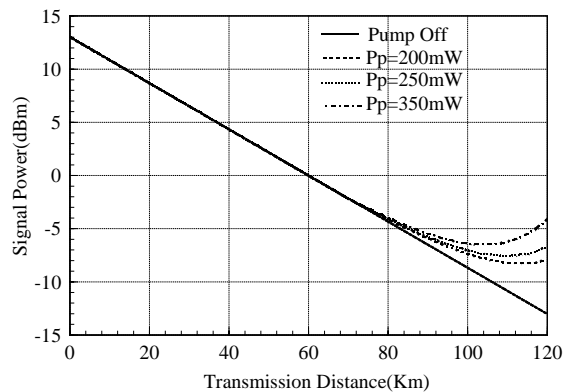Fig.5. Calculated signal power variation in a conventional DRA system.

Fig.6(a) Variation of signal power when a reflector is used to reflect the Pump-1.

The calculated results when a reflector placed at distance, L_1 from the transmitter and the expanded scale are shown in Fig.6(a),(b).

When L_1=70Km and pump power of 300mW, an improvement of more than 1dB in the received power can be expected. When the reflector is placed at 80Km or 90Km distance, the power level at the receiver is improved, but this will not improve the CNR performance.
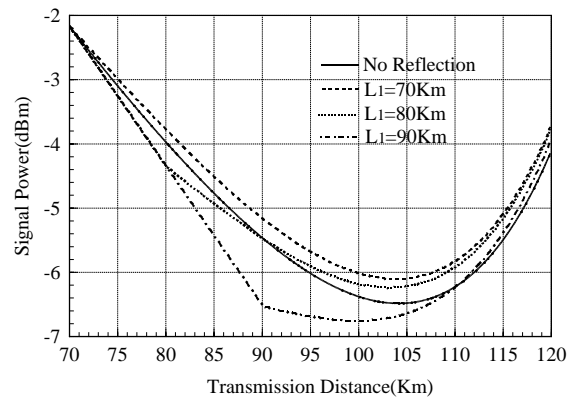

Fig.6(b) Expanded scale of Fig.6(a).

As a further improvement, we considered a second pump (Pump-2) at the same distance, L_1. Fig.7 shows the results, when Pump-2 of 100mW and 200mW at L_1=70Km are used. We can compare the difference between the cases of with and without Pump-1 reflection from the results shown in Fig.8. Although it is advantageous to have a reflector to reflect Pump-1, addition of Pump-2 with only moderate pump power is observed to yield better system performance.
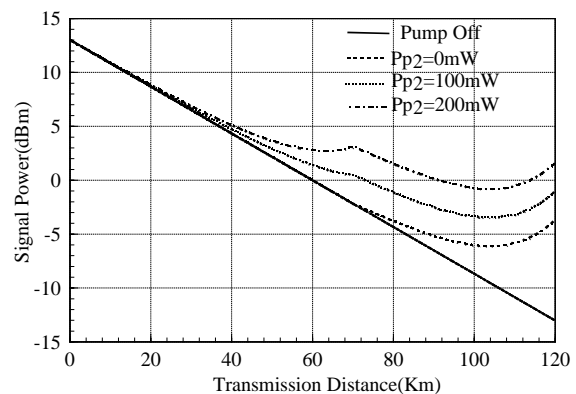

Fig.7 Signal variation when reflector and 2nd pump are used. Pump-1=300mW and L_1=70Km

The calculated results show that, even with moderate Pump-2 power, signal level at the receiver and also along the link is kept high as compared to the conventional DRA system. Received optical power of –1dBm and 1.6dB can be obtained with Pump-2 power of 100mW and 200mW respectively. The overall Raman gain
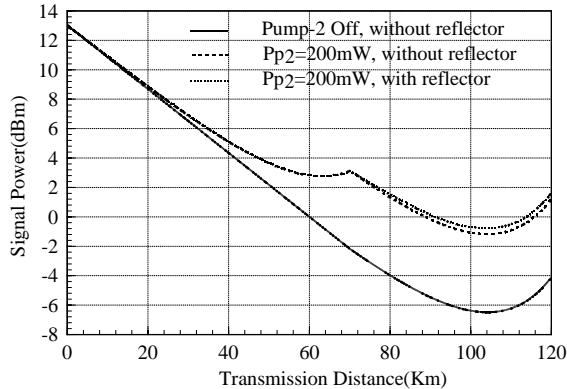
with this system is 14.6dB.

Fig.8 Comparison of signal variation with Pump-2, and with and without Pump-1 reflection

When the number of analog channels is limited, a CNR of more than 50dB is possible to be realized. Higher CNR performance is expected because the distributed Raman amplification system is used in the trunk line and the received signal will further be distributed to the subscribers. Therefore, a higher CNR performance expected for the above long distance CATV analog signal transmission system proves advantageous.

VI. CONCLUSIONS

In this paper, we presented the results of our investigation on the analog CATV signals and propose techniques to improve the system. We showed high performance of analog transmission is possible with a restricted number of analog channels. We proposed techniques using optimum pumping schemes to improve the system performance. The effects that limit the system performance turn out to be several scattering effects [5]. Bi-directional and higher order pumping schemes have been reported in the literature to improve the noise performance of DRA system [6]. The current trend in the CATV network is the migration from analog to digital video transmission and in the future one can expect very few analog channels, and thus systems based on distributed Raman amplification can be expected more promising. In the future, we will conduct analysis on the noise

characteristics of the system for analog CATV signals for improved noise performance.

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