Analysis on the Channel Power Oscillation in the Closed WDM Ring Network with the Channel Power Equalizer

Pilhan Kim, Sungho Bae, Seong Joon Ahn, and Namkyoo Park

Abstract—**Channel power oscillations in an optically amplified wavelength-division-multiplexed (WDM) ring network have been analyzed to reveal the oscillation dynamics and governing parameters of the chaotic behavior. The WDM ring round-trip frequency determined by the closed ring network span length and the speed of the channel power equalizer were found to be the two main factors defining the network stability. Spectral analysis shows that the formerly unresolved chaotic ring network behavior can be understood in terms of mode-locking-like instability which takes a closed WDM ring network as a loss-modulated laser.**

Index Terms—**Equalizers, network reliability, wavelength division multiplexing.**

I. Introduction

CHANNEL power oscillations with chaotic patterns have been reported in closed wavelength-division-multiplexed (WDM) rings [1]–[4]. The closed optical paths could be made in the process of channel add/drop reconfiguration at wavelength routing elements, or from the formation of optical cycles in the network [7]. The oscillations can create various problems in network management and control by making the transmitted signal channel power unstable and introducing additional noise. In the worst case, severe reduction of the signal power could cause false alarms at channel monitors even though there is no fault in the network [3]. While there have been increased concerns and experimental studies about the network oscillation phenomena in the optically amplified ring networks for this reason, still the precise dynamics of the network oscillation phenomena have not been clearly identified due to the difficulties in adjusting various experimental parameters.

In this paper, we study the optically amplified ring network with unclamped erbium-doped fiber amplifiers (EDFAs) and channel power equalizers (CPEs), to reveal the inner dynamics of the chaotic oscillation phenomenon. Numerical analysis shows that the chaotic lasing phenomenon occurs only in a particular range of the CPE *RC* time constant, and we find for the first time that this range of the *RC* time constant is again a function of the total ring network span length. Spectral analysis of the data also provides clues on the dominating time constants (WDM ring round-trip time and erbium lifetime, as well as CPE response times) and their effects on the oscillation. Our result suggests that the oscillation can be understood in terms of mode-locking-like instability, where the CPE is the loss-modulation source, the EDFAs the gain medium, and a closed loop the laser cavity.

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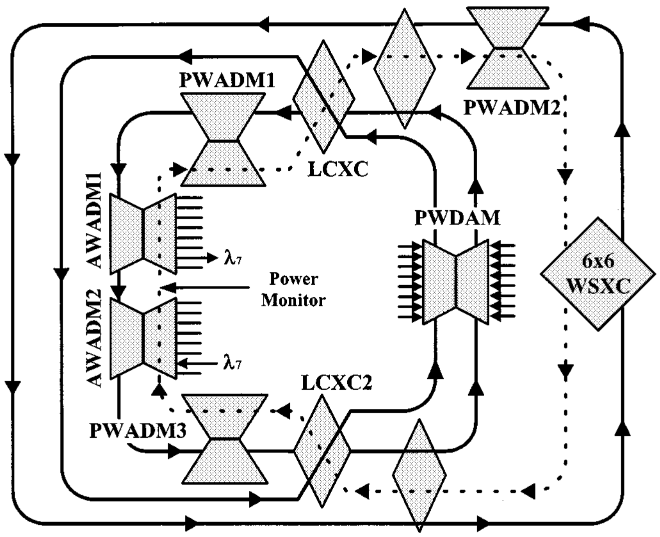

Fig. 1. Configuration of the MONET LEC-TB. The closed loop is marked with dashed lines (P-WADM: passive wavelength add/drop multiplexer; A-WADM: active wavelength add/drop multiplexer (the difference is whether or not it includes CPEs); LCXC: liquid crystal cross-connect; WSXC: wavelength selective cross-connect).

II. System Configurations

We used the configuration of MONET (multiwavelength optical network) LEC-TB (local exchange carrier testbed) at Bellcore shown in Fig. 1 for the simulation [1]. Two active wavelength add/drop multiplexers (A-WADMs) with CPEs and three passive WADMs (P-WADM) without CPEs were included in the 200-km WDM ring, forming a closed optical path. The length between two active WADMs was set to be 25 km. CPEs, which were used to maintain channel powers to the reference value, were modeled as variable attenuators controlled by feedback loops [5], and the unclamped in-line EDFAs were modeled as two-level atomic systems following average inversion analysis [6]. Input powers for the in-line EDFA were set at -20 dBm/channel, assuming a total of eight channels. Each EDFA was optimized so that the total round-trip gain could compensate for the network span loss. At $t = 0.1$ ms, we closed one of the signal channels to form a

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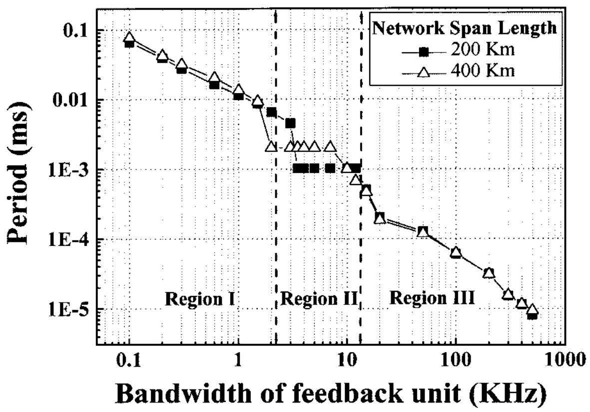


Fig. 2. Period of lasing power as a function of the bandwidth of the feedback circuit unit in a CPE (for single unit).

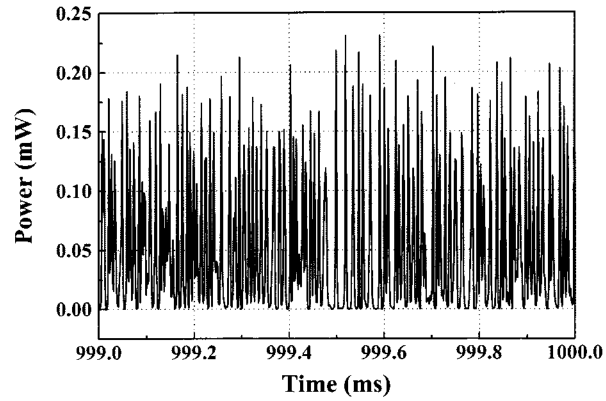
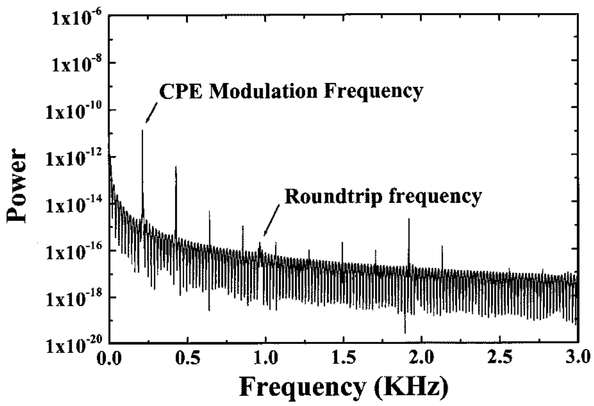


Fig. 3. Chaotic lasing patterns in Region III.

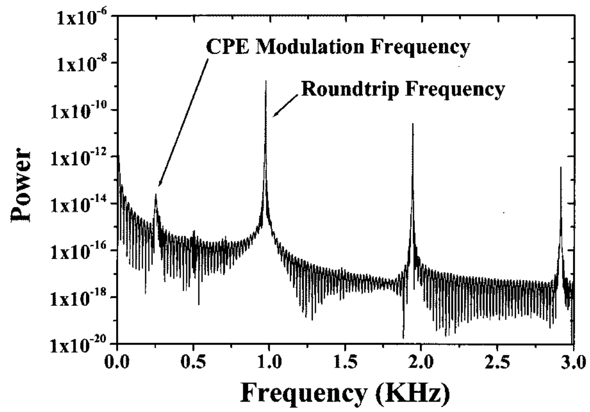
closed cycle, while leaving the other channels' path unchanged. To obtain sufficient resolution for the data in both the time and frequency domains, simulation time (in terms of real physical dynamics) was set up to 10 s with 2-μs time steps. Accuracy of the simulation has been confirmed by reproducing all the previous behaviors in the former experimental studies [1].

III. Result

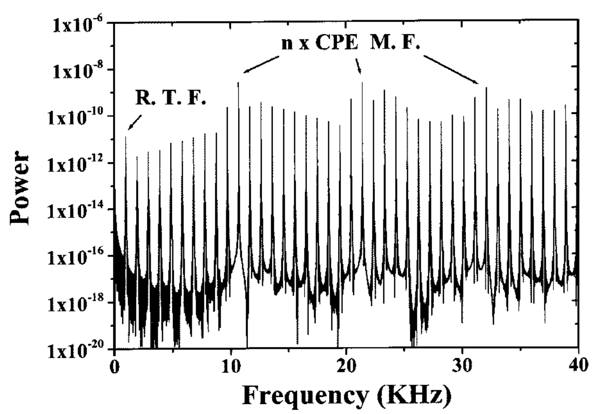
To investigate the dominating time constants, the analysis has been carried out mainly as a function of CPE time constants. Other time constants, fixed in nature such as erbium lifetime and loop round-trip time, were also changed to between 8.5$\sim$12.5 and 1$\sim$2 ms (200 and 400 km loop), respectively, to also see possible dependencies. The total network loop loss (transmission fiber/attenuator loss) were set to an equal value for different network length conditions for this specific report in order to remove the EDFA saturation dependency but just to show the loop length dependency. Fig. 2 shows the observed period and average magnitude of the channel power oscillation as a function of the bandwidth of feedback circuitry unit in CPE (determined by CPE *RC* time constant and is closely related with speed of CPE), for different network loop lengths. In Region I, where the CPE response time is significantly longer than the loop round-trip time, the signal oscillation frequency in the network increased following the CPE response bandwidth, without serious spiking behavior. This evolution of the network and response of signals in this domain (Region I) thus can be explained by the adiabatic adjustment in the network loop loss, where the loss-modulation frequency is much smaller than the loop round-trip frequency. Mode-locking behavior thus cannot occur here, to align the phase of different pseudolasing modes inside the cavity. Meanwhile, as the CPE response frequency was increased further, we observed a sudden reduction in the channel oscillation period to 1 or 2 ms, depending on the round-trip times of the assumed networks (200 and 400 km). After this transition point (in Region II), the channel oscillation period was then locked to a constant value showing mode-locking-like behavior, with multiple pulse series appearing at the mode-locked frequency with regular patterns. The peak-to-peak power variations of the signal pulse became much larger when compared to those in Region I and increased further as the CPE response frequency increased, reaching its maximum near the boundary of Region II and Region III. The most chaotic behaviors were then observed in Region III, where the CPE response frequency and network oscillation period were much higher than the loop round-trip frequency. The power fluctuation exhibited unstable chaotic behaviors (Fig. 3), while the pulse repetition period decreased again as a function of the CPE *RC* time constants. In closer inspection, we also found that the channel output power evolution still contains some regularity in terms of repetition rate, showing pulses of different magnitude at the period of a WDM ring network round-trip time or its submultiples. This seemingly unpredictable behavior can be understood in a better way when looked at from the spectral domain. The fast Fourier transform spectrum taken from the channel output power evolutions are plotted in Fig. 4(a)–(c), for Regions I to III, respectively. The most dominant feature from those pictures is the resonance peaks at the multiples of the loop round-trip frequencies, appearing at $n \times 1$ kHz (200 km). These peaks also appeared at $n \times 0.5$ kHz in the case of network span length 400 km, confirming the loop length dependency. Also shown in Fig. 4(c) is the higher-order spectral component of approximately equal magnitude to the fundamental order round-trip frequency component and overmodulation over resonance peaks with the CPE response frequency, providing the clues for the chaotic behavior. The largest peak at the round-trip frequency (1 kHz) over higher-order resonance peaks and relatively much smaller peaks at the multiples of CPE modulation frequency in Fig. 4(b) explain the rather regular spiking behavior in Region II as well. Additional investigation from other time evolution data with the above spectral analysis actually shows that the CPE response frequency and loop round-trip frequency are almost equal at the boundary of Regions II and III. Explained in more detail, the CPEs drive the loop loss at the subharmonics of the loop round-trip time in Region II, leading the network to be locked at the pulsed operation mode. For Region III, where the CPEs operate at a much faster speed than the loop cavity time, the CPEs overmodulate the loss of the loop at higher multiples of the loop characteristic frequencies and lead the network to operate at higher harmonics of the mode-locked operation, or into chaos. This dependence of the channel output power to the round-trip frequency confirms the effect of the WDM link span length to the chaotic behavior, in conjunction with the CPE response time. These large power fluctuations are thus the result of the resonance between



(a)



(b)



(c)

Fig. 4. Spectrum of lasing power. (a) Region I. (b) Region II. (c) Region III. Network span length 200 km. (CPE M. F.: Channel power equalizer modulation frequency. R. T. F.: round-trip frequency.)

the round-trip frequency and the CPE response. Overall, we conclude that these chaotic channel power oscillations can be interpreted as the signature of the mode-locking behavior with the WDM ring as the laser cavity and in-line EDFAs as gain elements, driven by loss-modulation elements such as CPEs.

IV. Summary

The chaotic oscillation effect in EDFA-amplified WDM ring networks in relation to the *RC* time constant of CPEs, and the network span length has been analyzed. We confirm that the reason for the chaotic oscillation behavior is the loss modulation by CPEs, as demonstrated in previous experimental reports [1]. We also found through spectral analysis that the chaotic behavior of the network oscillation can be explained in terms of mode-locking-like instability of the closed WDM ring network, where the CPEs act as loss-modulation sources, EDFAs as the gain medium, and a closed cycle in the ring network as a laser cavity. The distinctive resonance peaks in the spectral domain at the network round-trip frequency supports our explanation on this behavior. This result suggests that the length of the WDM ring link should be included as one of the key parameters in designing network elements and selecting right components for the survivable amplified EDFA ring networks.

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