Optics Communications 407 (2018) 63–68

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Chirp-aided power fading mitigation for upstream 100 km full-range long reach PON with DBR DML

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ARTICLE INFO

Keywords:
Power fading
Chirp
Directly modulated laser
Gain bias
Long reach PON

ABSTRACT

The DML is a promising option for cost-sensitive ONUs in optical access networks, but suffers from severe power fading due to dispersion and chirp. In this work, we investigate to mitigate the power fading by optimizing the chirp. Theoretical analysis indicates, a see-saw effect, influenced by the bias, exists between the adiabatic notch-induced fading (A-fading) and the transient notch-induced fading (T-fading). High bias can mitigate T-fading, but causes large A-fading. Low bias can avoid A-fading, but cannot completely mitigate T-fading. For each transmission distance, balance should be achieved to favor transmission. The ∼20 km short distance requires high bias to obtain large adiabatic chirp to counteract the T-fading, while the ∼100 km long distance requires relatively low bias to avoid the A-fading. With this power fading mitigation technique, we conduct upstream transmission experiment of LR-PON. Experiments show that, although signal contamination is inevitable, clear “1” and “0” are obtained with this power fading mitigation scheme for any 0∼100 km distance with 10 Gb/s OOK signal and DBR DML. The optical power budget penalty induced by 0∼100 km fiber is limited within only 2.2 dB, with optimum bias for each distance. More than 10 and 15 dB improvement is achieved when BER is 10^{-3} and 10^{-6}. A method is also proposed to automatically obtain optimum bias from the ranging procedure of PON protocol.

1. Introduction

In recent years, aiming to consolidate the access and metro networks, long-reach passive optical network (LR-PON) is drawing lots of attention from industry and academia [1–5]. On the other hand, researchers consider the use of cost-effective transmitters in PON system, such as directly modulated laser (DML) and electro absorption modulated laser (EML) for cost-sensitive optical network units (ONUs) [6,7]. However, for transmitting signals at the data rate of 10 Gb/s and beyond, these cost-effective transmitters suffer from interaction between fiber's dispersion and the intrinsic frequency chirping, which causes severe frequency power fading and limit the maximum transmission distance to much less than 100 km [8]. This issue is even more severe for DMLs, since the electrical radio frequency (RF) signal is directly applied to DML's gain section, leading to large frequency chirping.

To deal with power fading problem, one method is to employ extra advanced electrical or optical signal processing, such as multi-code interference (MCI) cancellation and delay interference based optical processing [9–12]. Another promising method is to manage the chirp property. In [13], distributed Bragg reflector (DBR) DML with 2.5 Gb/s directly-modulated signal for 120 km transmission is realized by taking advantage of the negative frequency chirp of phase section to counteract the positive frequency chirp of gain section. In [8], the bias voltage of the EAM is adjusted to balance the trade-off between the transient chirp parameter and the transferring linearity of the EAM, thus to alleviate the power fading. In [14], a theoretical investigation is conducted to DML's application to OFDM system and shines some light that by applying large bias current, adiabatic chirp can be enlarged to compensate the transient chirp dip for DMLs.

Particularly, some previous experimental studies have shown that, a higher bias current will improve transmission performance in some conditions [15,16], but they only adopted fixed high bias current in their experiments. Also, as shown in Fig. 4(b) of [17], even though a 100 km distance can be realized for TWDM-PON with DML only, but the performance of 20 km distance is bad, which cannot satisfy

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http://dx.doi.org/10.1016/j.optcom.2017.09.011
Received 20 June 2017; Received in revised form 4 September 2017; Accepted 4 September 2017

Table 1
Parameter definitions and their values of the DBR DML in this work.

Symbols	Parameters	Values
α	Linewidth enhancement factor	3.8
ε	Gain compression factor	1.1×10^{-23} m^3
Γ	Confinement factor	0.15
e	Elementary charge	1.6×10^{-19} C
V	Active layer volume	3×10^{-17} m^3
I_{th}	Threshold current	29 mA
γ	Constant, defined as: $\pi D\lambda^2/c$	$3.37 \times 10\text{–}25$ s^2/m ($\lambda = 1550$ nm)

the differential reach requirement of point-to-multi-point optical access networks.

In this paper, we investigate to mitigate the power fading by optimizing the DMLs' chirp which is simply achieved by adjusting the bias current to the gain section, and propose to apply such power fading mitigation technique to LR-PON. In the scheme, different bias currents are applied for different transmission distances, and full range reach for LR-PON is realized. The studies are conducted both theoretically and experimentally. It is found that, a see-saw effect exists between the two kinds of fading (A-fading and T-fading) in DML-based transmission systems. The dominance of A-fading and T-fading is different for different transmission distances. For each transmission distance, balance should be achieved to favor transmission. When transmission distance is 20 km, high bias current is required to increase the adiabatic chirp in order to counteract the T-fading @∼6 GHz, which is consistent with previous studies [15,16]. However, for a long transmission distance of 100 km, it is found that lower bias current is required to avoid the A-fading @0 GHz, which is not analyzed in the previous works. We investigate the balance between the A-fading and T-fading in this work. With the proposed power fading mitigation technique, we conduct upstream transmission experiment of LR-PON. We adopt 3-section DBR DML here, since it has ∼10 nm large tuning range and ns-level fast tuning time, which are significant for colorless operation in multi-wavelength LR-PON and dynamic load-balance or load-converging as specified in G.989 standard [1,13,18,19]. The experimental results show only 2.2 dB optical power budget (OPB) penalty is introduced by fiber transmission from 0 to 100 km with 10 Gb/s NRZ-OOK signals. The phenomenon of power fading presented in the experiment is consistent with the theoretical results. Compared with using extra optical processing or heavy electrical digital signal processing, the scheme is much simpler and more cost-effective. Furthermore, we propose a method to automatically obtain optimum bias current from the ranging procedure of current PON MAC protocol.

2. Technical principles

The frequency response transfer function of an optical fiber transmission system based on DMLs can be expressed as [15,20,21],

$$
\begin{aligned}
H(f, L, I) &= \sqrt{\alpha^2 + 1}\cos\left(\gamma L f^2 + \tan^{-1}\alpha\right) \\
&\quad + j\frac{\alpha\varepsilon\Gamma\left(I - I_{th}\right)}{2\pi f e V}\sin\left(\gamma L f^2\right) \\
&= H_{tst}(f, L) + H_{adb}(f, L, I). \qquad (1)
\end{aligned}
$$

In this equation, the first term $H_{tst}(f, L)$ denotes the frequency response induced by the transient chirp (transient response), and the second term $H_{adb}(f, L, I)$ denotes the frequency response induced by the adiabatic chirp (adiabatic response). f is the frequency, L is the transmission distance and I is the bias current. The definitions of other parameters, as well as the corresponding values of the DBR DML used in this work, are listed in Table 1.

For Eq. (1), it is obvious that, for a given distance, $H_{tst}(f, L)$ is fixed while $H_{adb}(f, L, I)$ varies with different bias currents. With the values in Table 1, $\left|H_{tst}(f, L)\right|$, $\left|H_{adb}(f, L, I)\right|$ and $\left|H(f, L, I)\right|$ are plotted in Fig. 1. It is shown that, both adiabatic response and transient response suffer from severe power notches after fiber transmission. For simplicity, notches in the adiabatic response are noted as adiabatic notch while notches in the transient response are noted as transient notch, as is shown in Fig. 1(a). The fading in the total response curve of $H(f, L, I)$ is induced by a combination of the adiabatic notch and the transient notch. Due to the periodical feature of Sine and Cosine function, there exist multiple power notches in the response curve, as Fig. 1(c) shows. The fading induced by adiabatic notch is noted as A-fading while the fading induced by transient notch is noted as T-fading. Clearly, with the increase of transmission distance, both kinds of fading tend to emerge at a lower frequency, which limits the transmission distance. This can also be understood from Eq. (1) that f^2 is inversely proportional to L. It is worth mentioning that, we only need to focus on the first A-fading (@0 GHz) and the first T-fading in the following context, because both of the second A-fading and the second T-fading appear beyond the bandwidth of 10G class optics even when transmission distance is 100 km (around 8–9 GHz), as Fig. 1(c) depicts.

2.1. The see-saw effect between the A-fading and the T-fading with the Bias

For any distance, the first transient notch which induces T-fading is located in the passband, while the first adiabatic notch which induces A-fading is located at 0 GHz. In the following, we will analyze the power variation of the two kinds of fading with the bias current.

When bias is low, it is shown that the T-fading has major destruction to the total response curve, and the A-fading is submerged by transient response. Taking 20 km transmission distance as an example shown in Fig. 1(a), when bias is 70 mA, the T-fading at ∼6 GHz is very obvious. The maximum power difference from 0 GHz point is ∼7 dB, which will inevitably degrade the transmission performance. When bias gets higher, the adiabatic response can gradually compensate the T-fading, and even provide power gain. It is shown in Fig. 1(a) that, at 6 GHz point, 130 mA bias shows ∼10 dB improvement than 70 mA bias. So it will be beneficial to increase the bias current to mitigate the T-fading.

However, with the increase of bias current, the adiabatic response also makes the A-fading at 0 GHz severe. This phenomenon is not obvious in short transmission distance, but can be easily witnessed in long transmission case where the frequency response curve is much more squeezed. In Fig. 1(c), it is shown that, when bias is 130 mA, the response curve is severely out of shape, leading to ∼15 dB power difference between the 0 GHz frequency part and the high frequency part. Such unflatten frequency response might result in harmful influence to BER performance. In this way, it turns out that the A-fading might become the dominant restriction factor for 100 km distance case.

To summarize, though high bias can mitigate the T-fading, it also makes the A-fading more obvious. Thus, with the variation of bias current, there is a see-saw effect between the A-fading and T-fading.

2.2. Bias selection for different distances

For optical access networks, different ONUs have different distances from the OLT. The see-saw effect provides a method to mitigate the power fading for the ONU transmitters by adapting different bias currents according to transmission distance.

Firstly, for 20 km transmission condition of Fig. 1(a), since large bias current provides power gain for the adiabatic response and compensates for the T-fading at 6 GHz, it can be inferred that high bias current (110–130 mA) might be chosen to achieve better transmission performance. Secondly, for 40 km transmission condition, the response curve for 40 km condition is much squeezed compared with 20 km condition. The T-fading is easier to be compensated by the adiabatic chirp, such that a moderate bias current will be acceptable compared with 20 km condition. Lastly, for 100 km transmission condition, the frequency response is further squeezed. In this condition, since the 130 mA bias causes ∼15 dB A-fading at 0 GHz than high frequency part, power gain at high frequency part might be sacrificed, and relatively low bias is required to avoid the severe A-fading at 0 GHz. In the following, we will examine the principle by experiments and discuss its application in LR-PON.