Research on characterization of frequency chirp in RSOA

Junfang Shang (尚军芳), Jian Chen (陈 健)*, Rujian Lin (林如俭),

Yingxiong Song (宋英雄), and Yingchun Li (李迎春)

Key Laboratory of Specialty Fiber Optics and Optical Access Networks,

Shanghai University, Shanghai 200072, China

*Corresponding author: chenjian@shu.edu.cn

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Light chirp is a major issue in optical fiber links. This letter deals with precise characterizations of the frequency chirp parameters of reflective semiconductor optical amplifiers (RSOAs). The RSOA chirp properties are represented by transient and adiabatic chirps, whose parameters are characterized utilizing a ratio between the phase and the amplitude modulation depths of the RSOA when modulated with sine waves. Utilizing a high-resolution optical spectrum analyzer, a RSOA linewidth enhancement factor α and an adiabatic factor k are obtained experimentally, based on which the influence of chirp parameters on the transmission performance of non-return-to-zero (NRZ) signals can be analyzed.

Reflective semiconductor optical amplifiers (RSOAs) have been utilized as intensity modulator in adaptively modulated optical orthogonal frequency division multiplexing (OFDM) modems recently[1]. With salient advantages such as simultaneous signal modulation and optical amplification, provision of centralized colorless wavelength management and bidirectional transmission, the employment of RSOAs in optical network units (ONUs) has been extensively investigated[2,3]. A large number of research papers have been published, few articles have, however, been dedicated to address the frequency chirp issues associated with RSOAs.

An important effect arises from a laser is that the output optical frequency varies with the change of a driving current, known as the frequency chirp[4]. The light chirp and its dependence on optical power is one of most relevant issues in laser-based optical systems. It has been extensively studied from the beginning of the laser history[5].

The main interest in chirp properties has been shown for lasers[4], but a relatively less interest for RSOAs. A laser output lightwave envelope contains the information to be transmitted when driven above the threshold current. Under direct intensity modulation, the laser suffers a considerable spectral broadening because of the residual frequency modulation produced by chirp, which is determined by the transient and adiabatic chirp parameters[6]. Due to the same composition material as laser and similar resonant cavity structure, we believe that RSOA also has similar chirp characteristics.

Frequency chirp is a manifest drawback in OFDM transmission systems, especially in optical networks[7]. For example, its interaction with fiber chromatic dispersion introduces a limitation to link distance, and determines the ultimate transmission bandwidth of single-mode fiber systems. Therefore, it is of great importance to address the physical origin of frequency chirps in RSOAs.

In this letter, we precisely measure chirp parameters of RSOAs with a simple method. By comparing the measured spectra with calculated results, we characterize the frequency chirp parameters of RSOAs. In particular, the linewidth enhancement factor α, which is the main parameter describing chirp, is extensively discussed.

The relation between the light chirp and the optical power can be seen as the instantaneous change of optical frequency Δv in response to variations of optical power, i.e. the intensity-modulated light wave is parasitically frequency modulated. The frequency chirp Δv can be expressed as[8]

$$\Delta(t) = \frac{1}{2\pi}\frac{\mathrm{d}\phi(t)}{\mathrm{d}t} = \frac{\alpha}{4\pi}\left[\frac{1}{p(t)}\frac{\mathrm{d}p(t)}{\mathrm{d}t} + kp(t)\right], \quad (1)$$

where $p(t)$ is the instantaneous optical power, and $\varphi(t)$ is the instantaneous optical phase. When the modulation frequencies exceed 100 MHz, these two main contributions to $\Delta v(t)$ can be distinguished, and the thermal effects can be omitted[9]. The $\mathrm{d}p(t)/\mathrm{d}t$ component represents the transient chirp which is scaled by α, often called as the linewidth enhancement factor (dimensionless). The adiabatic chirp term $kp(t)$ produces a frequency shift proportional to the instantaneous optical power, and the proportional constant k is associated with the nonlinear gain (dimension GHz/mW)[10].

In digital transmission, $kp(t)$ arises due to the change between a long sequence of "1" and a long sequence "0". As a direct result, Eq. (1) is suitable for describing frequency chirp characteristics of both RSOAs and semiconductor lasers. These effects are confirmed by our experimental measurements shown in this letter. From the measurements of the optical intensity spectrum, we can obtain both the transient and adiabatic chirp parameters. The complex susceptibility of the gain medium of the RSOA gives rise to a phase modulation (PM) when the RSOA is intensity modulated. In this letter, we measured the ratio between the residual PM depth and amplitude modulation (AM) depth of the RSOA driven by a sine signal at frequency f. The output optical intensity is given by[6]

$$I \cong I_0(1 + m\cos(2\pi ft))\text{with } m \ll 1, \quad (2)$$

where I_0 is the optical carrier intensity corresponding to the center wavelength, and m is the intensity modulation depth. The definition of m is the ratio between of the peak variation of the instantaneous optical intensity and the average optical intensity when the driving sine wave has a constant amplitude A. For detailed analysis, we express the function of RSOA optical gain versus bias current I_b as a polynomial with the coefficients a, b, c, d, e by fitting to the measured data of optical powers at different bias currents[11]. As an example, for a specific $P_{in}=0$ dBm, the fitting function $Y(I) = a + bI_b + cI_b^2 + dI_b^3 + eI_b^4$ is a four-order polynomial and a, b, c, d, e are optimum coefficients of the polynomial as listed in Table 1. It should be noted that the coefficients are only effective for a given injection optical power.

Figure 1 shows the RSOA optical gain versus bias currents for various optical injection powers. The stronger input optical power causes the deeper saturation of optical gain.

In addition, the intensity modulation depth m of the RSOA is expressed as[11]

$$m = \frac{\widehat{P}}{P_0} = \frac{[\mathrm{d}Y/\mathrm{d}I]_{I=I_b} A}{Y(I_b)} = \frac{b + 2cI_b + 3dI_b^2 + 4eI_b^3}{a + bI_b + cI_b^2 + dI_b^3 + eI_b^4} A. \quad (3)$$

The average power of two first-order sidebands is given by[6,8]

$$\overline{I_{\pm 1}} \cong I_0 (\frac{m}{4})^2 (1 + (\frac{2p}{m})^2) \text{ with } m \ll 1, \quad (4)$$

where p is the optical residual PM factor, which jointly decides the power of optical sidebands with m due to a PM to AM conversion process in the optical gain media, and is related to the transient and adiabatic chirp

Table 1. Optimum Parameter Values of the fitting Function

Fitting Unction:	$Y(I) = a + bI_b + cI_b^2 + dI_b^3 + eI_b^4$
Parameters	Optimum Value
a	-23.8453108884568 (dB)
b	0.997412685854602 (dB/mA)
c	-0.00908323107802423 (dB/mA^2)
d	4.0092712642751e-5 (dB/mA^3)
e	-6.77992638011861e-8 (dB/mA^4)

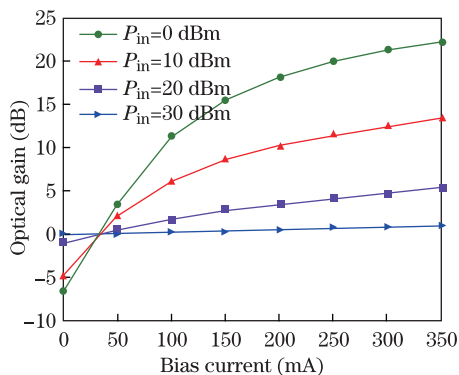Fig. 1. Optical gain of RSOA.

parameters, and defined as[8]

$$\frac{2p}{m} = \alpha \sqrt{(1 + (\frac{f_c}{f})^2} = \alpha \sqrt{1 + (\frac{k}{2\pi f} I_0)^2}, \quad (5)$$

where f_c and f present the chirp frequency and the modulation frequency. For $f_c \ll f$, we have $\alpha = 2p/m$, which is a familiar expression. As shown in Eq. (5), $2p/m$ is a measure of the frequency chirp of a specific transmission system. Clearly a large frequency chirp degrades the performance of the optical transmission system due to the optical phase noise enhancement.

As Eq. (1) can be used to describe the chirp characteristics of a RSOA, Eqs. (4) and (5) can be derived directly from Eq. (1)[8], so they can also be used for the RSOA.

For a given frequency f and a modulation depth m, $2p/m$ can be obtained by taking the measured power of the two first order sidebands into Eq. (4). According to Eq. (5), numerical fitting is finally undertaken to obtain the average value of α. By using the second part of Eq. (5), and the available value α, k can be calculated. Ultimately chirp characteristic of the RSOA is completely described.

In this letter, we measured the characteristics of a RSOA with bias current ranged from 30 to 100 mA. The RSOA model (SOA-RL-OEC-1550-TO, CIP Technologies, UK) is packaged in Shanghai. A commercially available DFB laser provides an optical signal injected into the RSOA. We measured the optical power of the carrier and the modulation sidebands with an APEX AP2041B high resolution optical spectrum analyzer (OSA). The experimental setup adopted here is shown in Fig. 2, where the oscilloscope (HP Infinium 4 Gb/s) is used for checking the transmitted waveforms.

We can determine the peak current of the sine wave that drives the RSOA by measuring the output power of the signal source. According to Eq. (3), a specific m is obtainable by adjusting A and I_b.

A measured optical spectrum using the high resolution OSA for a 600-MHz sine wave modulated RSOA with a 2.2% modulation depth is shown in Fig. 3. The second order sidebands are negligible due to their power values being 30 dB lower than the first order ones for the modulation depth used.

The OSA used here allows the measurements of the optical spectrum at modulation frequencies below 100 MHz. This is particular useful for the present RSOA, as the modulation bandwidth of the RSOA is as small as 1.5 GHz. Therefore, the modulation frequencies used for the measurements are set to vary in a range from 50 MHz to 1.2 GHz.
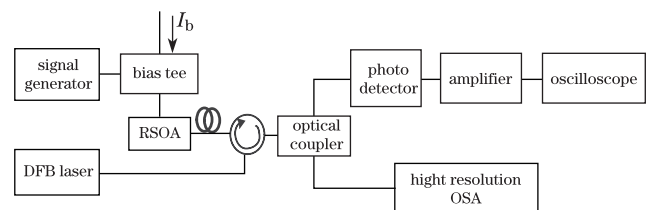

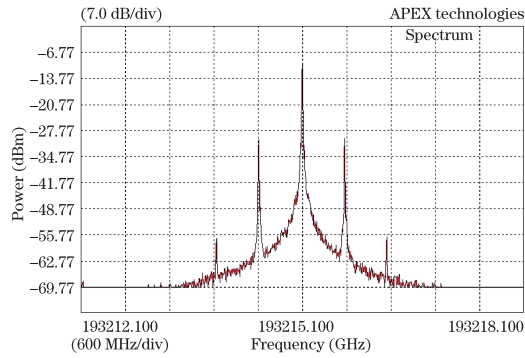Fig. 2. Experimental setup for the measurement.

Fig. 3. Measured spectrum of RSOA under 100-MHz sine amplitude modulation with 2.2% modulation depth.
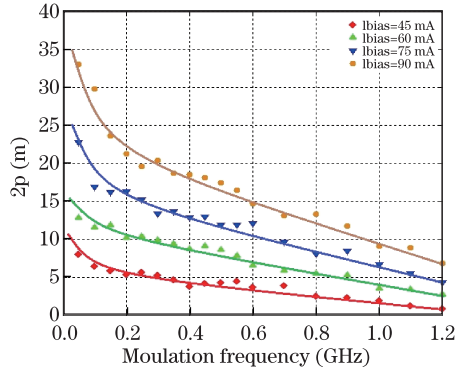

Fig. 4. Measurement result of $2p/m$ for different bias conditions and modulation frequencies.

The choice of the dynamic range of the modulation depth is also very critical if m reaches an irrational value, the difference between the first and second order sidebands is not more than 30 dB, and the modulation on the RSOA is then invalid, so the value of m should be kept rational. Therefore in our measurements, the values of m are taken from 2% to 5%, which are within the dynamic range enabling the validity of Eq. (5).

The measured value $2p/m$ as a function of modulation frequency is shown in Fig. 4 for different RSOA bias conditions. We measured four sets of data. The solid curves represent the numerical fitting of the measured data using Eq. (5).

Due to the bandwidth limitations of the RSOA and in order to ensure the high accuracy of the measured data, we set the highest modulation frequency at 1.2 GHz. It is shown in Fig. 4 that the factor $2p/m$ increases with the increase of bias current and decreases with the increase of modulation frequency. Further increase in modulation frequency ultimately gives rise to an occurrence of an almost constant value. Then we use an unlimited approximation method to calculate the values of α and k by curve fitting, and the obtained results are shown in Fig. 5.

As seen in Fig. 5, α gradually increases with the bias current I_b and k changes in the range of 13.57 ± 1.05 GHz/mW. The corresponding values of α and k are summarized in Table 2. It is shown in both Fig. 5 and Table 2 that the chirp parameter α depends on the bias current. k varies in a range of ± 1.05 GHz/mW, mainly resulting from the residual reflection of the collimation lens inserted in front of the RSOA chip. Such refraction
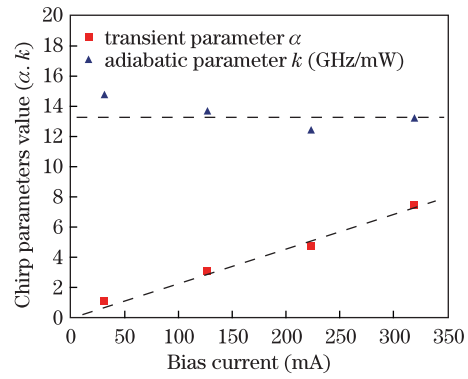

Fig. 5. Calculated parameter values from curve fitting to Eq. (5).

Table 2. Corresponding Values of α and k

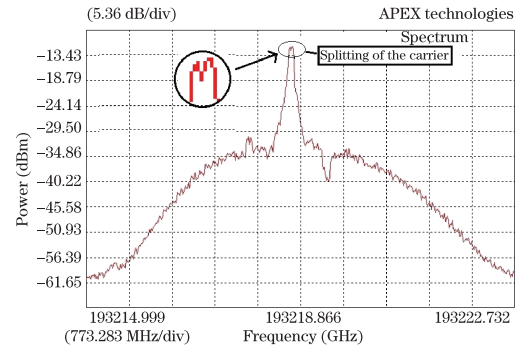| I_b	45	60	75	90
α	1.01	3.04	4.72	7.43
k (GHz/Mw)	14.72	13.57	12.53	13.27

Fig. 6. Measured spectrum of RSOA modulated by 250 Mbps NRZ with peak to peak 49mA between '1' and '0' level.

alters the output optical power and thus causes the variation of k values, as suggested by Eq. (1).

The obtained value of α can be verified with measurements using a method reported in Ref. [12]. We have also verified k directly utilizing the optical spectrum in NRZ signal driving case. According Eq. (1), we know that the optical spectrum is different for digit '1s' and digit '0s' when the RSOA is modulated by a NRZ signal. The RSOA's refractive index corresponding to '0s' and '1s' are different, thus resulting in the occurrence of a large frequency chirp over the transient region, and more importantly, a frequency shift between '0s' and '1s' also appears, which can be observed in Fig. 6. The frequency shift is governed by

$$\Delta v('0' \leftrightarrow' 1') = \frac{\alpha k}{4\pi} \Delta P('0' \leftrightarrow' 1'). \tag{6}$$

As shown in the inset of Fig.6, when RSOA is modulated by a 250-Mbps NRZ signal with p-p amplitude of 49 mA, the measured split width of the spectral peak is 45 MHz. It should also be noted that the splitting of carrier caused by adiabatic chirp is a function of signal bit rate[13,14], and the splitting of carriers is more significant for lower bit rate cases where the adiabatic chirp is dominant (Fig. 6), whilst the splitting effect is not

pronounced for higher bit rate cases where the transient chirp effect becomes more important. The co-existence of the above-mentioned two effects achieves a certain balance between '1' and '0' levels, but a certain asymmetry exists. This asymmetry is due to the differences between '1' to '0' transition and '0' to '1' transition, including the complicated dependence on raising and falling edges, power levels and chirp values.

The chirp parameters depend on the saturation condition of RSOA. The stronger saturation will appear when the injection power is getting higher. In this case the variation of output instant power becomes limited, so that the adiabatic chip effect will be less important. This phenomenon can be viewed in Fig. 6, where the splitting width of peaks in optical spectrum is much smaller than the results for DFB laser reported in Ref. [6].

In conclusion, an approach for measuring frequency chirp parameters of RSOAs is implemented using a high-resolution OSA and a real-time oscilloscope. This leads to a precise characterization of the transient and adiabatic chirp effects, and allows the analysis of the performance affected by the frequency chirp in an optical transmission network based on RSOAs. The result shows good agreement with those measured using a linewidth-based method. Furthermore, the approach adopted in this letter can also be applied to other optical modulators.

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