Generation and coherent characteristics analysis of laser phase modulation spectrum by cascaded phase modulators*

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Laser phase modulation spectrum with 25 frequency bands is generated by modulating a single frequency laser with two cascaded phase modulators (PMs) with driving voltage amplitudes at 3.2 V and 7.8 V, respectively. And the time delay self-heterodyne method is adopted to measure and analyze the coherent characteristics of the original single frequency laser light and the generated multi-frequency light from two phase modulation schemes. By comparison of laser linewidth, the experimental results show that the laser phase modulation does not change the coherent characteristics of each frequency band, and the laser phase modulation spectra benefit the performance optimization for the Rayleigh scattering based optical fiber sensing system.

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Laser phase modulation technology has been widely used in optical fiber communication and sensing systems. By one phase modulator (PM), the vector millimeter-wave signal can be generated and used in the radio over fiber (RoF) communication system[1], and by control of the driving radio frequency (RF), multiple carriers can be obtained for passive optical networks (PONs) with ultra-dense frequency space. Based on an optical tapped delay line structure cascaded with a PM, an optical frequency comb (OFC) with arbitrary free spectrum range can be controllable[2]. In addition, by cascading PMs with combined harmonics[3] or Mach-Zehnder modulator[4], the flatness of the OFC can be greatly optimized. The cascaded PMs and dual-output dual-parallel Mach-Zehnder modulator were also used to generate simultaneous frequency and bandwidth doubling linearly chirped waveform for high resolution radar systems[5]. And then, in the optical fiber sensing technology, the PM is usually adopted to modulate the coherent laser source to obtain multi-frequency laser light. Coherent laser source has been used in distributed optical fiber sensing system to measure the fiber attenuation, temperature, strain, vibration parameters along the fiber under test. In the Rayleigh scattering based optical time domain reflectometry (OTDR), such as coherent OTDR and phase-sensitive OTDR, the fading noise of the Rayleigh scattering signal affects the performance of the sensors, and many methods have been adopted to reduce the fading noise. SUMIDA[6] proposed an M-ary frequency shift keying (FSK) probe to reduce the fluctuation of the OTDR trace, in which it simultaneously obtained 4 OTDR traces by 4 probe pulses with different carrier frequencies, and by data averaging, the trace fluctuation was reduced. IIDA et al[7] adopted a PM and arbitrary waveform generator (AWG) to modulate single frequency laser to get frequency multiplexing laser source to improve the measurement dynamic range (*DR*) and reduce the fading noise. Although the AWG sweeping method can obtain more than 200 frequency channels, it in itself is time-division multiplexing for probe sending and sensing signal receiving. LU et al[8] employed the phase modulation method to obtain multi-frequency laser light in coherent OTDR, and at different modulation depths (*MDs*), the dual-frequency probe light, three Freque-ncy probe light[9] and four-symmetrical-frequency probe light[10] are generated, and they can both benefit the fading noise reduction and *DR* enhancement of the coherent OTDR system. In addition, the laser phase modulation method is also adopted in the phase-sensitive OTDR (φ-OTDR). With three-frequency-probe light, the interference fading noise can be effectively reduced and the φ-OTDR obtains much accurate event identification ability[11]. The multi-frequency laser light generated by PM with time serial frequency pulse driving[8] benefits for the phase information extraction by corresponding data processing algorithm improvement to suppress the influence of Rayleigh fading noise[12] and the cross-talk noise between adjacent frequency channels[13]. What is

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more, the multi-frequency light by phase modulation of a single frequency laser can also improve the stimulated Brillouin scattering threshold[14], so as to make the optical fiber sensing system keep excellent performance. Above all, the fading noise suppression is a hot issue in the Rayleigh scattering based sensors[8-16].

As is known, the multi-frequency light generated by phase modulation of single frequency laser light has important value for the sensing system *DR* enhancement and fading noise reduction[7-14], so it is necessary to study its coherent characteristics, and discuss whether the fading noise suppression effect originates from the degradation of the laser coherence. What's more, if the phase modulation method does not change the coherence of each frequency band in the multi-frequency light, it can be inferred that much better laser source can be generated by cascaded PMs for the application of optical fiber sensing system[3-5]. Therefore, in this paper the laser coherent characteristics by phase modulation are studied, and by one PM and two cascaded PMs respectively, different multi-frequency laser sources are generated. For the laser coherent characteristics analysis, the time delay self-heterodyne method is employed to measure the laser linewidth[17,18].

By time delay self-heterodyne method, the phase modulation spectra symmetrically distribute with center frequency at about 200 MHz, and each frequency order in the spectra can be accurately measured and analyzed. And by the laser linewidth comparison with the original single frequency laser and each frequency band in the multi-frequency laser, it is found that laser phase modulation does not change the coherence of each frequency band in the multi-frequency laser light. So, by adjusting the modulation voltages, more frequency bands with close light power are obtained, which benefits the fading noise reduction in the Rayleigh scattering based optical fiber sensing system[7-14].

The experimental setup is shown in Fig.1. The coherent laser light is launched into the optical coupler 1 with light splitting ratio of 90: 10, and then the output light with higher power comes into the acousto-optical modulator (AOM: T-M200-0.1C2J-3-F2S, Gooch &Housego), which up-shifts the laser frequency about 200 MHz, and then the laser light is input into the polarization controller (PC) so that the light polarization state matches with polarization parameters of the polarization maintaining optical fibers of PM1 and PM2. Two cascaded PMs (MPX-LN-0.1, iXblue) are adopted in the experiment, as it is convenient for analyzing the laser phase modulation spectra with only one PM and the two cascaded schemes. The PM2 links an optical fiber section with length of 50 km, which is used as the optical fiber delay line. And then, the output light mixes with another output light from the optical coupler 1 in the optical fiber coupler 2. The optical fiber coupler 2 is an X-type 3 dB coupler, and the light from its two output ports has 180° phase shift, so that the balanced photodetector (BPD: 435C, Thorlabs) transfers the carrier signal with very high common mode rejection ratio (*CMRR*). The electrical bandwidth of the BPD adopted in the experiment is 350 MHz. The BPD links the electrical spectrum analyzer (ESA: N9020A, Keysight Technologies), and then the laser self-heterodyne spectra and laser linewidth can be measured.

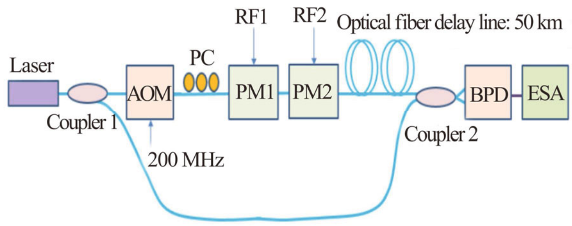

Fig.1 Experimental setup for laser phase modulation spectrum measurement and analysis

For the time delay self-heterodyne method to measure laser linewidth, the spectra obtained by the ESA can be expressed by[17]

$$S_0(\omega)=\exp(-\Delta\omega\tau_{\rm d})\delta(\omega)+\frac{2\Delta\omega}{\Delta\omega^2+\omega^2}\times\{1-\exp(-\Delta\omega\tau_{\rm d})[\cos(\omega\tau_{\rm d})+\frac{\Delta\omega}{\omega}\sin(\omega\tau_{\rm d})]\},\quad(1)$$

where $\Delta\omega=2\pi/\tau_{\rm c}$, and ω is the angular frequency deviated from the carrier angular frequency $\omega_{\rm AOM}$, $\tau_{\rm c}$ is the coherent time of the laser source, and $\tau_{\rm d}$ is the delayed time by the optical fiber delay line. So, theoretically if $\tau_{\rm d}\gg\tau_{\rm c}$, then $\exp(-\Delta\omega\tau_{\rm d})\sim0$, $\omega\tau_{\rm d}\sim0$, and Eq.(1) can be written as

$$S_0(\omega)=\frac{2\Delta\omega}{\Delta\omega^2+\omega^2}.\quad(2)$$

Therefore, the spectra on the ESA become perfect Lorentzian line shape with width equal to twice of the laser optical spectral width[18]. Fig.2 shows the self-heterodyne spectrum of the single frequency laser source, and the laser linewidth at 20 dB below the peak is 16.6 kHz, which means that the 3 dB linewidth is 1.66 kHz[18]. Generally, the laser coherence is presented by the 3 dB linewidth which is also called as the full width at half maximum (*FWHM*).

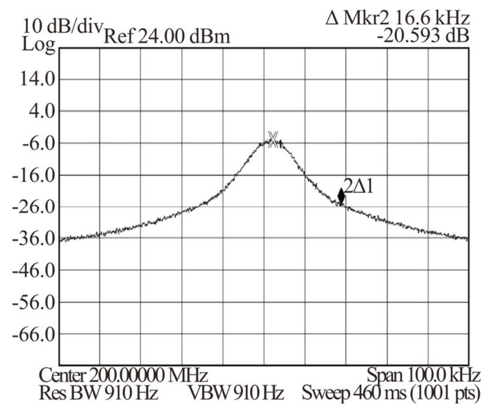

Fig.2 Self-heterodyne spectrum of the single frequency laser source

And then the coherent characteristics of laser phase modulation spectra are studied. When the laser passes through the photoelectric crystal in the PM, the phase of the light wave will be modulated. Assuming that the electric field of the input light is $E_{\mathrm{in}}=A_{\mathrm{I}}\exp(\mathrm{j}\omega t)$, the phase change $\phi(t)$ will occur after being modulated by the PM, and then the output optical field becomes $E_{\mathrm{out}}=A_{\mathrm{O}}\exp[\mathrm{j}\omega t+\phi(t)]$, where A_{I}, A_{O} and ω are the corresponding amplitudes and angular frequency of input and output optical fields from the PM, and $\phi(t)$ is the modulation phase that adds to the input optical field. $\phi(t)=U_{\mathrm{m}}\sin(\omega_{\mathrm{m}}t)$, and U_{m} and ω_{m} are the amplitude and angular frequency of the RF driving voltage, respectively. By Fourier analysis, the optical field output from the PM can be written as follows

$$E_{\mathrm{out}}=A_{\mathrm{O}}\exp(\mathrm{j}\omega t)\exp(U_{\mathrm{m}}\sin(\omega_{\mathrm{m}}t))=$$
$$A_{\mathrm{O}}\exp(\mathrm{j}\omega t)\sum_{q=-\infty}^{+\infty}J_q(U_{\mathrm{m}})\exp(\mathrm{j}q\omega_{\mathrm{m}}t)=$$
$$A_{\mathrm{O}}\sum_{q=-\infty}^{+\infty}J_q(U_{\mathrm{m}})\exp\{\mathrm{j}q(\omega+\omega_{\mathrm{m}})t\}, \tag{3}$$

where J_q is Bessel function, and q is integer number. From Eq.(3), it can be known that the single frequency laser source after phase modulation becomes multi-frequency light, and each frequency band is symmetrical about the zero-order frequency band. In addition, by two cascaded PMs, the output optical field is the phase modulation spectrum of each input frequency band from PM1, so that much more frequency bands can be obtained. And then different laser phase modulation spectra are obtained by adjusting the RF driving voltage of PM1[8-10]. The laser phase modulation spectrum by self-heterodyne method with *MD* at 1.435 and driving frequency at 21 MHz is shown in Fig.3. Theoretically, at this *MD*, the 0 and ±1st order frequencies are with the same power[8].

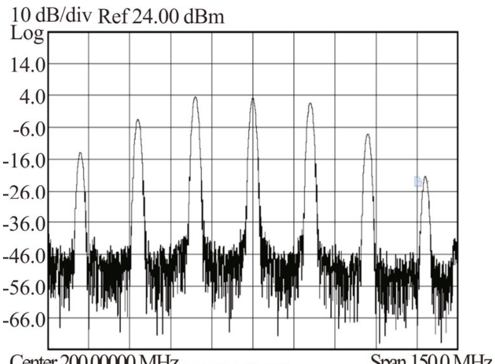

Fig.3 Laser phase modulation spectrum with *MD* at 1.435

In Fig.3, the frequency orders on the right are a little lower than the corresponding ones on the left, and we infer that it is caused by the insertion loss of the RF cable that links the BPD, because the transmission bandwidth of the RF cable is not wide enough. But it is certain that this deviation does not affect the laser linewidth measurement. So, by setting the center frequency to be analyzed in ESA to corresponding frequency band center, the 0, ±1st, ±2nd and ±3rd order frequency bands are measured, as shown in Figs.4—10. It can be seen from Fig.4 that the laser linewidth at 20 dB below the peak is 16.8 kHz, and it means that the laser linewidth (*FWHM*=3 dB) is 1.68 kHz[17,18].

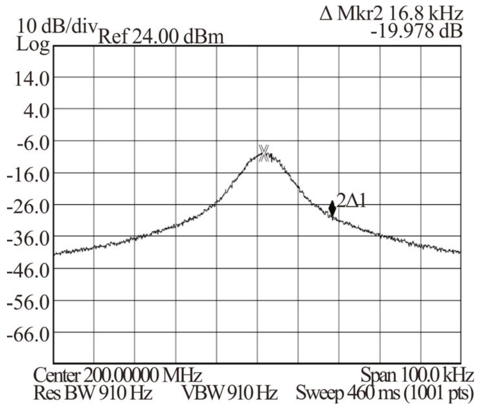

Fig.4 Spectrum of the zero-order frequency band

Fig.5 and Fig.6 show the laser line shape details of the −1st and +1st order frequency bands from Fig.3, and the linewidths are 1.65 kHz and 1.63 kHz, respectively.

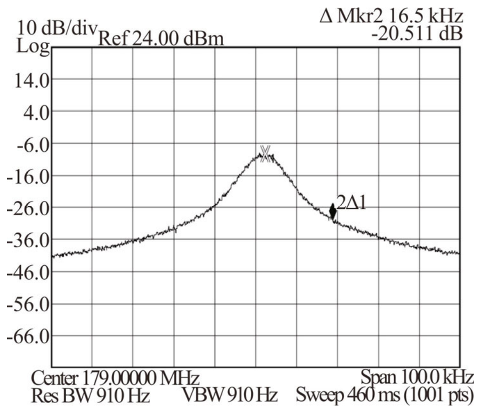

Fig.5 Spectrum of the −1st order frequency band

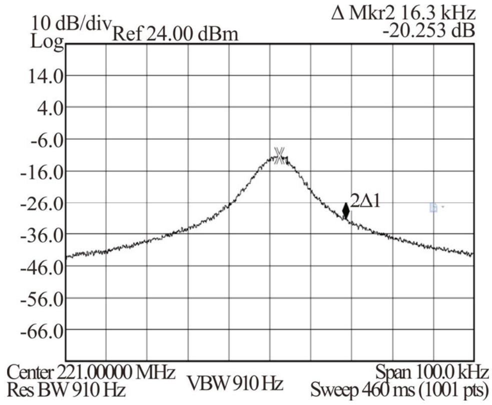

Fig.6 Spectrum of the +1st order frequency band

Fig.7 and Fig.8 show the laser line shape details of the −2nd and +2nd order frequency bands in Fig.3, and the linewidths are 1.69 kHz and 1.68 kHz, respectively. And also, in Fig.9 and Fig.10, the measured laser linewidths of the −3rd and +3rd order frequency bands are 1.68 kHz and 1.65 kHz, respectively.

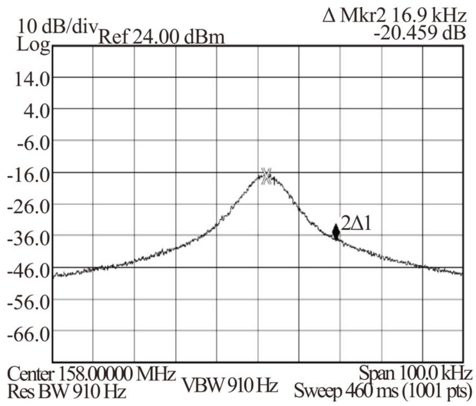

Fig.7 Spectrum of the −2nd order frequency band

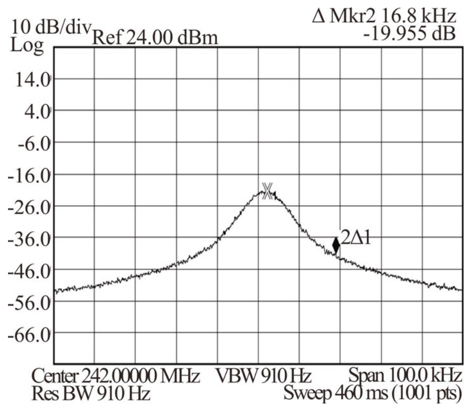

Fig.8 Spectrum of the +2nd order frequency band

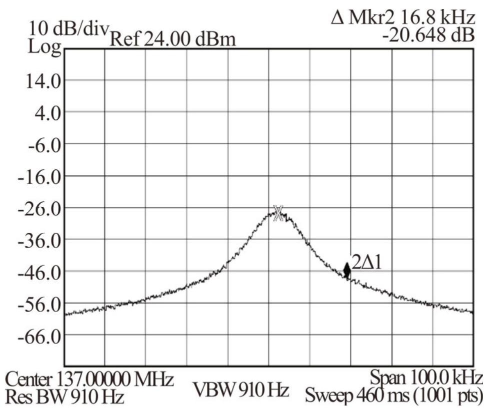

Fig.9 Spectrum of the −3rd order frequency band

As to the multi-frequency light, it can be seen from Fig.4 to Fig.10 that the laser linewidth of each frequency band ranges from 1.63 kHz to 1.68 kHz, which are very close to the linewidth value of the original laser source. Therefore, considering the linewidth fluctuation of the original single frequency laser source, it can be concluded that the phase modulation method does not change laser linewidth of each frequency band, and it means that the laser coherence of each frequency band in the phase modulation spectra keeps the same with the single frequency laser source. To obtain multi-frequency laser light for optical fiber sensing application, two cascaded PMs are adopted. The driving voltage of PM1 is set at 3.2 V, and then, by adjusting the driving voltage of the PM2, the power of the frequency bands in the phase modulation spectra changes. As the function generator (DG1022U, RIGOL) used in the experiment can output a maximum RF frequency of 25 MHz, the driving frequency of PM1 is set at 21 MHz, and to make each frequency band with the same interval, the driving frequency of the PM2 is set at 3 MHz. When the driving voltage of the PM2 is set at 7.8 V, 25 frequency bands with 1 MHz frequency interval and less power deviation are obtained as shown in Fig.11.

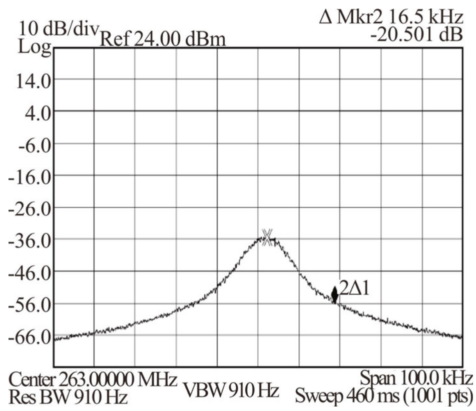

Fig.10 Spectrum of the +3rd order frequency band

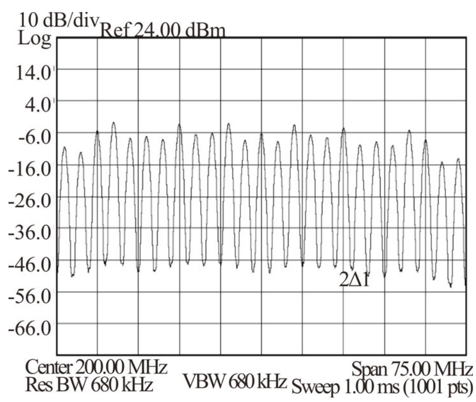

Fig.11 Laser phase modulation spectrum by two cascaded PMs

The linewidth of each frequency band in Fig.11 is observed, and it also demonstrates that the laser coherence of each frequency band in the phase modulation spectra keeps the same with the original single frequency laser source. The multi-frequency laser source obtained by laser phase modulation or by multi-wavelength laser sources such as Fabry-Perot (F-P) laser has been used in distributed optical fiber systems[12,13], and it is believed that the multi-frequency laser source generated by phase modulation has much wider application, because it is essential to heterodyne detection scheme to improve the detectable sensitivity and reduce the fading noise of the Rayleigh scattering[8-14]. In addition, the signal extraction in each frequency band is relatively convenient[6-10], and processing and analyzing the signal of each frequency band will enhance the measurement *DR* and accuracy for event identification along the sensing fiber under test[12-16].

In conclusion, by the time delay self-heterodyne method for laser linewidth measurement, the characteristics of the phase modulation spectra of a single frequency laser are experimentally tested and compared with one PM and two cascaded PM modulation schemes with independent RF driving voltages. The experimental results show that laser phase modulation does not change the coherence of each frequency band generated. And by cascading phase modulation with RF driving voltage amplitudes at 3.2 V and 7.8 V respectively, a multi-frequency laser source with 25 frequency bands is obtained, which benefits the Rayleigh scattering based optical fiber sensing applications.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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