Hyperfine spectral structure of semiconductor lasers

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In this paper, we propose an interference technique that can provide a quantitative and ultrafine-resolution spectral analysis because the optical heterodyning is performed at nonzero frequency and interfering waves propagate in optical fiber. The spectrum of a laser consists of a large number of wave trains. Our study is focused on the features of wave trains. We demonstrate that wave trains emitting simultaneously have random frequency spacings, and the probability of occurrence of two or more joint wave trains with the same frequency is high. The estimated linewidth of the wave train is narrower than 1 mHz, corresponding to a wavelength range of 10^{-23} m.

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INTRODUCTION

Understanding the spectral structure of semiconductor lasers is a fundamental issue. Spectral analysis, especially of the fine spectral structure, reveals the important properties of semiconductor lasers, such as mode characteristics, atom emission behavior, high-frequency performance, and coherence features.

The wave train is a concept proposed several decades ago [1–4], and it has been accepted widely for analyzing the static and dynamic performance of lasers. Many efforts have been made to measure the laser coherence length [5–10], which is regarded as the length of the wave train. However, a complete description of other properties, such as linewidth, intensity profile, and frequency spacings among wave trains, has not been explicitly given due to resolution limitations in both measuring techniques and instruments. For example, wave trains were idealized to be all identical for simplicity, i.e., having the same length (or duration time) [4]. Based on the atom emission law [11], the rise and decay times are not identical. This has been observed in the measurement of the intensity profile of an ultrafast pulse [12]. Although wave trains are supposed not to be strictly monochromatic [4], experimental demonstration is extremely difficult and has not been reported to date. Traditional spectral analysis is based on division of the wave front or division of the amplitude [1]. Michelson-interferometer-based methods have been widely used for optical spectral analysis [5–10], and a resolving power of 10^5 can be achieved. These methods [5,6,10] suffer from mechanical vibration, thermal and acoustic fluctuations, and beam divergence, and errors in the observation of the spatial coherence are difficult to eliminate [13]. This limits the resolution in the observation of fringe visibility, and makes it impossible to analyze the fine spectral structure of lasers. The ultimate spectral linewidth of a real light wave source was predicted to be 2 mHz [13]. This means that a resolving power of 10^{17} is needed in optical spectral analysis.

In this paper, we use an interference technique based on the division of frequency to characterize the wave trains of semiconductor lasers, and present a spectral structure model in the frequency domain. The assumptions for the model are demonstrated through a series of experiments.

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EXPERIMENTAL DEMONSTRATION

The commonly used method for spectral analysis has been two-beam or multiple-beam interference. In general, there are two methods to obtain beams from a light wave source: division of the wave front and division of the amplitude [1]. Our frequency-division scheme shown in Fig. 1(a) is used to measure the linewidth of the wave train. This method allows us to perform optical heterodyning at nonzero frequency. This makes it possible to measure the linewidth of the wave train with a high-resolution electrical spectrum analyzer instead of observing the fringe visibility. Here, we must point out that the linewidth of the wave train is completely different from the spectral linewidth of the laser (the effective frequency range of the Fourier spectrum) [1]. The linewidth of a laser is determined by the bias current and the cavity quality of the laser structure [10], and is broadened mainly by the rapid shift of the resonance frequency caused by thermal and acoustic fluctuations and the change in the real and imaginary parts of the refractive index with carrier density [13,14].

From the measured spectrum shown in Fig. 1(b) one can see that the linewidth of the beat signal between the light waves from different sources is around 16 MHz, corresponding to the spectral linewidth of the DFB LD. The linewidth of the beat signal at the modulation frequency is very narrow (about 10 Hz), and this phenomenon was observed 15 years ago [15,16]. In addition, it was found that the measured linewidth of the modulation source was about 10 Hz. We believe that this narrow beat signal comes from the interference between the coherent wave trains in the carrier and the sidebands of the intensity-modulated light wave. To precisely estimate the linewidth of the wave trains, a pure electrical source and a high-resolution spectrum analyzer are used. The experimental results plotted in Fig. 1(c) show that the measured 10 dB linewidths of both the electrical source and the beat signal are about 1.1 mHz. Because no obvious broadening is observed for the optical beat signal, the linewidth of

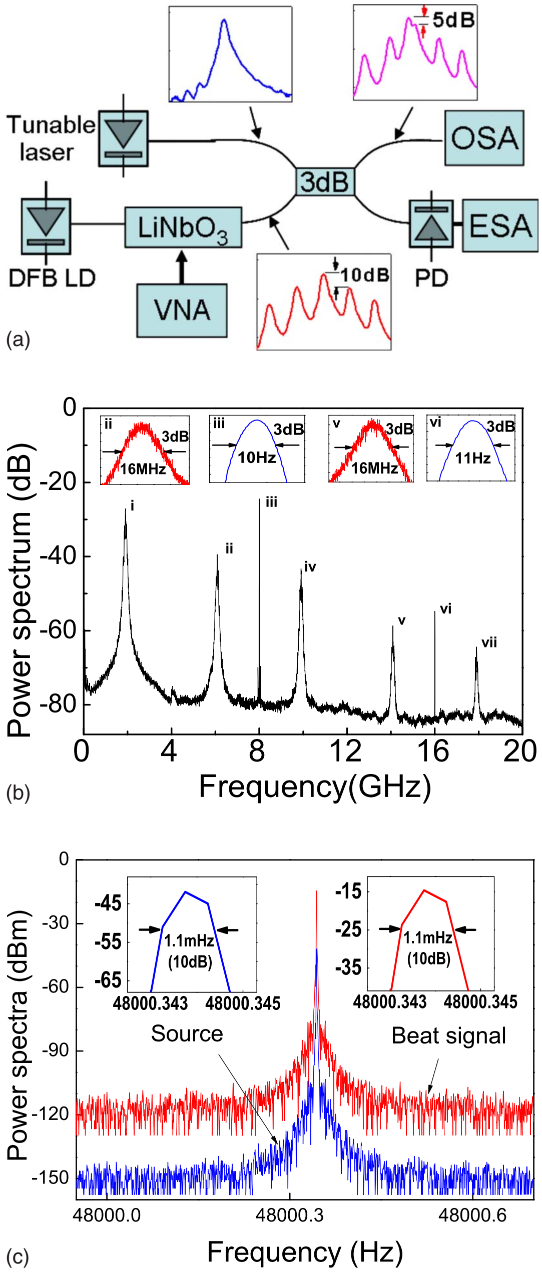

FIG. 1. (Color online) Spectral linewidth analysis of light wave source and wave trains. (a) Experimental setup with the typical optical spectra measured using an optical spectrum analyzer (OSA). A 1.55 μm distributed feedback laser diode (DFB LD) was biased at 100 mA. A narrow linewidth (<100 kHz) tunable laser was used as reference light wave source, and its wavelength was tuned to be 1.9 GHz lower than that of the DFB LD. A vector network analyzer (VNA, Agilent 8722ET, 50 MHz–40 GHz) is operated at 8 GHz with an output power of −15 dBm. The $LiNbO_3$ modulator was operated in its linear range. An R&S FSP30 electrical spectrum analyzer (ESA) was used for spectral measurement. (b) Measured power spectrum of the beat signal. Insets are the higher-resolution spectra. (c) Measured hyperfine spectrum compared with the power spectrum of the wave form generator, where an Agilent 35670A two-channel ESA, which has the highest-resolution bandwidth available commercially to date, was used instead, and the modulation source was a wave form generator Agilent 33250A (80 MHz).

the wave train should be less than 1 mHz. Therefore, the proposed method can achieve a resolving power of 10^{17}.

Comparing Figs. 1(b) and 1(c) one can see that the measured linewidth of the beat signal changes with the linewidth of the modulation source. However, this measurement is still limited by the stability and resolution of the spectrum analyzer; finer spectral structure analysis can be achieved with improvement of the experimental apparatus. Even under these limitations, the experimental results clearly show that the spectral linewidth of the wave train is extremely narrow (<1 mHz) and different from the spectral linewidth of the laser, which is typically of the order of 10 MHz.

From the measured optical and power spectra shown in Fig. 1, one can see that the optical power of the reference signal is 5 dB higher than that of the carrier in the signal channel. However, peak (ii) (beating between the lower sideband and the reference signal) is 15 dB lower than peak (iii) (beating between the first sidebands and the carrier in the signal channel). The 17 dB ($5+15-3=17$) discrepancy is understandable because the beat signal between the wave train in the carrier and the corresponding wave trains in the first sidebands is always superposed at the modulation frequency. This experiment also verifies that the wave trains emitting simultaneously have random frequency spacings. If this is not the case, the beat signal at the modulation frequency cannot have such a narrow linewidth and a 55 dB signal-noise-ratio (SNR) as shown in Fig. 1(b).

We use the experimental setup shown in Fig. 2(a) to investigate the interference between light waves from the same laser source when a path difference exists. The optical intensity of the reference signal is 15 dB higher than that of the carrier in the signal channel. When the Mach-Zehnder (MZ) fiber interferometer is symmetric, the carrier and sidebands are all in phase. In this case, adding the reference signal increases the carrier amplitude and the beat signal reaches its peak value.

From Fig. 2(b) one can see that, when the fiber interferometer is made asymmetric, the beat peak decreases and the noise level increases with increasing path difference. This is because some wave trains in the reference channel, which have length shorter than the path difference, become incoherent with the corresponding wave trains in the sidebands in the signal channel. Interference among these incoherent wave trains produces beat signals whose frequencies spread around the modulation frequency randomly, and leads to an increase in noise level. This experiment implies that the wave trains have different temporal or spatial lengths. However, the results are not enough for estimating the length of wave train because the carrier still exists in the signal channel.

In order to estimate the length of the wave trains we propose a filtered MZ interferometer scheme as shown in Fig. 3(a). This all-fiber experimental setup is superior to the Michelson interferometer [1,10] because there is no problem of beam divergence [8,9]. For light waves from a real laser, atom emission is irregularly modified by the disturbance from its neighbors, and the duration of wave trains will vary randomly within a certain range. The function "Max Hold" of the equipment allows us to measure the peak values of the beat signals. Therefore, only the average length of the wave trains can be obtained in this experiment.

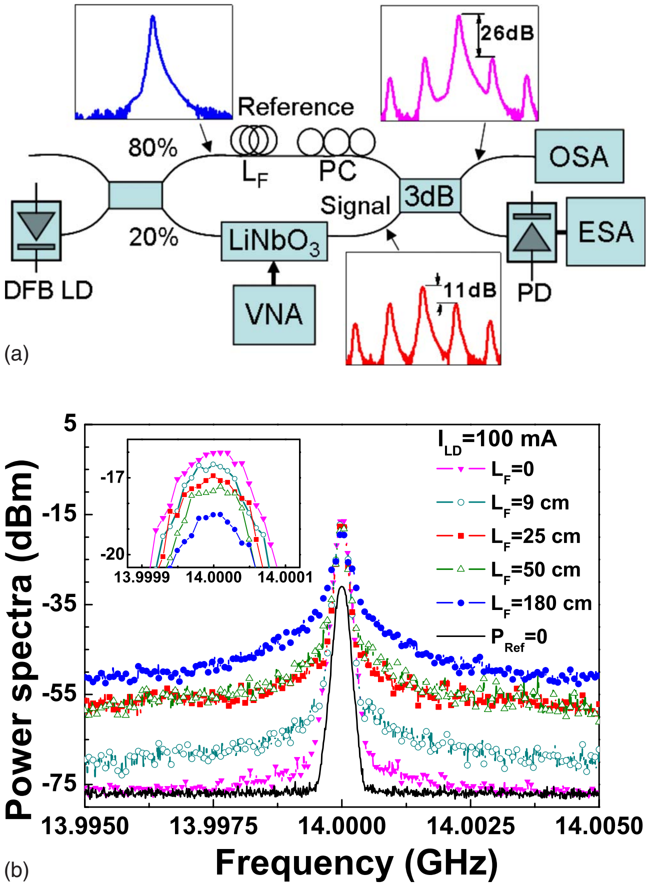

FIG. 2. (Color online) Investigation of interference between lightwaves from one laser source. (a) Experimental setup with the measured optical spectra. PC, polarization controller; L_F, the fiber length difference between two arms of the MZ interferometer. Light wave in the signal channel is modulated at 14 GHz and its intensity is fixed in the measurement. (b) Measured power spectra at various fiber length differences, where the optical beat signal is recorded using the function "Max Hold" of the ESA. The curve "$P_{\text{ref}}=0$" indicates the spectrum without reference signal injection. The inset shows the higher-resolution spectrum.

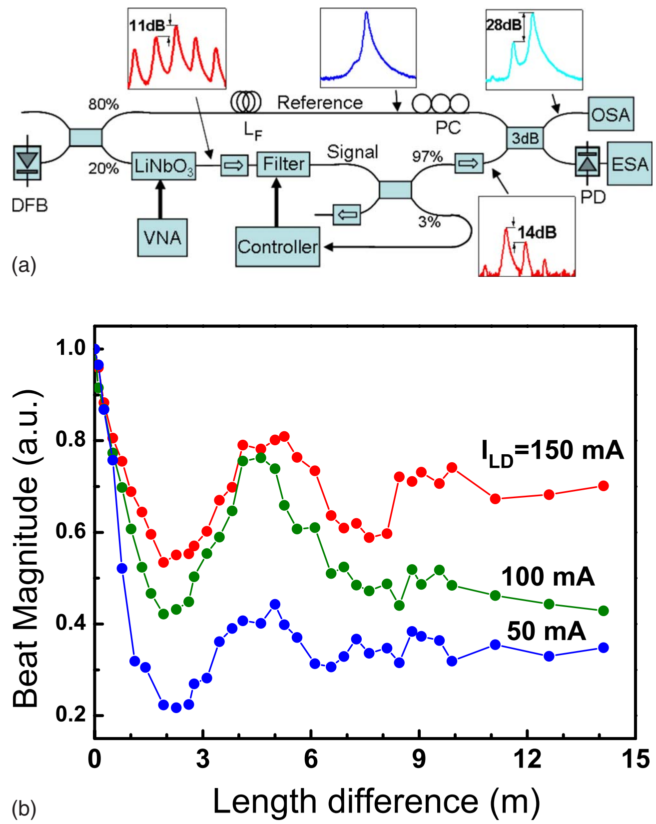

FIG. 3. (Color online) Estimation of coherence length. (a) Experimental setup with the measured optical spectra. A narrowband (2 GHz) optical filter is added to the setup [Fig. 2(a)] to remove the carrier signal in the signal channel. Three optical isolators are used for the filter to be locked to one of the first-order sidebands. (b) Measured magnitude of the beat signals at different fiber length differences when the DFB laser is biased at 50, 100, and 150 mA, respectively.

The results given in Fig. 3(b) show that the beat signals at different bias currents have a dip at the fiber length difference of 2.2 m, and a peak at 4.6 m. Another small peak at 9.2 m can also be observed, especially at high bias current. The dip and peak values increase with the bias current, but the locations do not change. The conventional models presented in the past literature are unable to explain this phenomenon. If all wave trains are identical and of simple form, the measured beat magnitude will decrease monotonically with increasing path difference. We assume that a wave train may seed another wave train with the same frequency before it vanishes. When the path difference is half the wave train length, the beat signal is at its minimal value. When the path difference is about the wave train length, the beat signal reaches its second peak. For the laser we measured, the average length of wave trains is estimated to be about 4.6 m.

Here we propose an alternative method for determining precisely the average coherence length. Figure 4(a) shows the typical setup for measuring the small-signal frequency response, from which the fiber dispersion and the chirp parameter of light emitter can be obtained [17]. We found that this setup can also be used to determine the length of the wave trains. After intensity modulation, the light wave is divided into the carrier and the sidebands, which have a frequency spacing precisely corresponding to the modulation frequency. The carrier and sidebands are treated as "interfering waves," and have different velocities due to the optical fiber dispersion. If the optical fiber dispersion is positive, the lower sideband is faster than the carrier, and the carrier is faster than the upper sideband. Therefore, a long optical fiber functions as an interferometer. The interference is extremely stable because the interfering waves propagate in the same medium (an optical fiber in our case). The path difference increases with the modulation frequency. For our purpose, large dispersion is desirable in order to increase the path difference. The dispersion coefficient of G652 fiber is only 16.9 ps nm^{-1} km^{-1}. To increase the path difference, the long fiber can be replaced by dispersion compensation fiber or a chirped fiber grating.

After optical-to-optical transmission calibration, the errors of a network analyzer together with the lightwave transmitter and receiver can be completely removed. From the measured frequency response shown in Fig. 4(b), the peak frequency f_p and the first and second dip frequencies f_{D1} and f_{D2} can be read out. The optical path difference of the carrier and sidebands at the pth peak frequency f_p can be expressed as

$$\Delta L_p = \frac{c}{f_p}\left(p - \frac{1}{2}\frac{f_{D2}^2 - 3f_{D1}^2}{f_{D2}^2 - f_{D1}^2}\right), \quad p = 0,1,2,3, \dots , \qquad (1)$$

where c is the light speed in free space. It is interesting to notice that ΔL_p depends only on the peak and dip frequencies, and it is not necessary to determine the physical length of the fiber and its dispersion coefficient.

The typical frequency responses using a 150 km G652 optical fiber and two chirped fiber gratings are plotted in Fig. 4(b), and the corresponding variations of the beat intensity with path difference are given in Fig. 4(c). When the path difference reaches 20 cm, the average beat signal decreases by 3 dB. During the observation time, the changes in modulation frequency and total fiber length can be neglected since the path difference is less than 25 cm after 150 km optical fiber transmission. Hence, this scheme is very suitable for the ultrafine spectral analysis of semiconductor lasers.

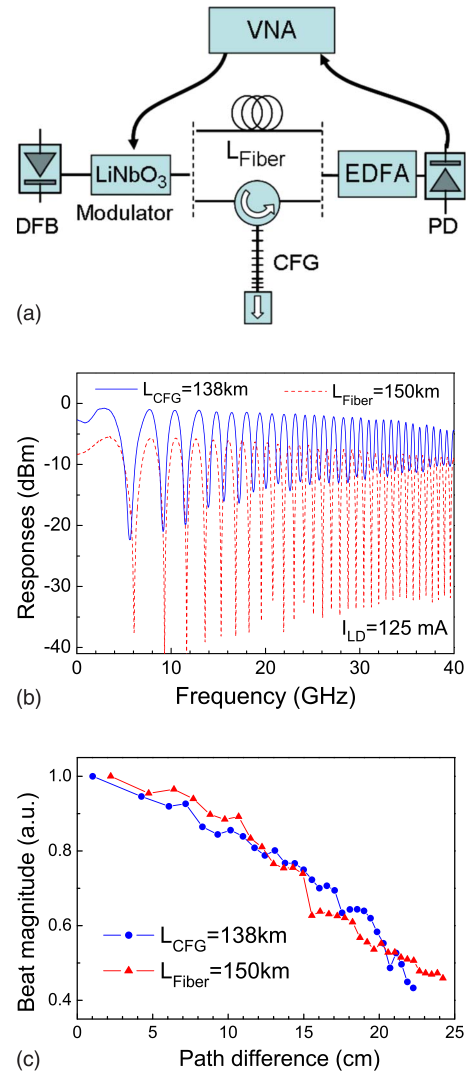

FIG. 4. (Color online) Estimation of coherence length. (a) Experimental setup, in which a long optical fiber or chirped fiber grating (CFG) can be used to achieve a path difference for the light waves with different frequencies. An erbium doped optical fiber amplitude (EDFA) is used to enlarge the input optical power into the photo detector (PD). (b) Measured frequency responses using a 150 km G652 optical fiber and two chirped fiber gratings for compensating the dispersion of 81+57 km G652 fiber when the DFB laser is biased at 125 mA. The measurements are made 50 times and the curves show the average values. (c) Normalized magnitudes of the corresponding beat signal peaks.

CONCLUSIONS

Our measurement technique provides the finest analysis of the optical spectral structure of semiconductor lasers to date, to our knowledge. Compared with the traditional spectral analysis using the Michelson interferometer, the proposed technique has several major advantages.

(a) It is possible to measure the beat signal at nonzero frequency with a higher-resolution spectrum analyzer. Therefore, quantitative analysis can be realized instead of just observation of spatial coherence.

(b) Interference between the carrier and the sidebands is very stable. The influences of mechanical vibration and thermal and acoustic fluctuations in the optical path length are very weak because both the carrier and the sidebands propagate in the same optical fiber.

(c) The resolving power of the Michelson interferometer is limited by the beam divergence. The resolving power is only 10^5. Our technique can achieve a relatively long optical path difference using a long optical fiber as the delay line. The resolving power can be 10^{17} or even higher.

Our study reveals the major features of wave trains and leads to an initial hyperfine spectral structure model in the frequency domain as follows.

(a) *Spectral linewidth*. The wave train is not strictly monochromatic and its spectral linewidth is narrower than 1 mHz, corresponding to a wavelength range of 10^{-23} m at 1.55 μm.

(b) *Intensity profile and duration*. The temporal and spatial intensity profiles of wave trains are neither identical nor of simple form. The length of the wave train has a large variable range. The average duration and intensity profile mainly depend on the laser structure, the optical cavity, and the bias condition.

(c) *Frequency spacings*. Wave trains emitted simultaneously have random frequency spacings. A wave train can seed another wave train with the same frequency, and the probability of occurrence of two or more joint wave trains with the same frequency is very high. The subsequent wave trains may have different frequencies, but the probability is much lower.

The established interference technique can achieve extremely high resolving power and allows us to get an insight into the hyperfine spectral structure of semiconductor lasers. We believe this method is also applicable to different types of lasers.

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