Measurement of the Swept-Frequency Carrier-Induced FM Response of a Semiconductor Laser Using an Incoherent Interferometric Technique

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Abstract—**The swept frequency deviation response of a distributed-feedback laser is measured using a new incoherent interferometric technique. Unlike previous interferometric techniques, this technique is independent of the phase relationship between the optical fields in the two interferometer paths. The theoretical background is discussed, and measurements yielding an FM deviation response of ±1 dB from 0.1 to 2.9 GHz with an efficiency of ~300 MHz/mA are reported for a 1.55 μm DFB laser.**

I. Introduction

FREQUENCY shift keying is now a viable alternative to ASK modulation in optical communication systems. Frequency modulation formats benefit from the amplitude-phase coupling process inherent in semiconductor lasers where modulation of the injection current results in frequency modulation of the optical field. Multielectrode laser structures introduce longitudinal inhomogenities allowing uniform FM response, increased FM efficiency or the possibility of FM modulation with suppressed intensity modulation [1], [2]. A number of factors, such as injection current bias, optical feedback, laser structure/material and modulation frequency can influence the FM response of the laser [3], [4]. The design of complex structure lasers requires powerful measurement techniques for rapid experimental evaluation of the FM response.

Measurements of the FM deviation frequency response have been performed either: point by point where the modulated electric field power spectrum is observed at successive modulation frequencies and the FM index β is found, or by using swept coherent interferometry techniques [4], [5]. Swept measurements are preferred but are complicated by the free spectral range and optical phase quadrature requirements for the interferometer. The purpose of this work is to propose a simple incoherent technique to measure the modulus of the swept deviation response of a single-frequency laser. With this new technique, an interferometer with a differential delay τ_0 much greater than the coherence time of the source is used. This results in a measurement that is independent of the optical phase between the combined fields in the interferometer. This technique is referred to as the swept delayed self-homodyne (S-DSH) technique, and its variation, the S-GDSH technique with gated modulation.

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II. Technique Description and Theory

The experimental block diagram is shown in Fig. 1. The DFB laser is biased well above threshold current. The emitted field of the DFB-LD passes through a GRIN rod lens, two Faraday effect isolators, and is focused onto a single-mode optical fiber. The optical field is then directed into two paths by the first fiber-optic coupler of the Mach–Zehnder interferometer, one path having a temporal delay τ_0 of 3.5 μs with respect to the other path. This time delay serves to decorrelate the combined fields. Next these two fields are combined in the second directional coupler and mixed on the high speed photodetector of the lightwave signal analyzer. The tracking generator applies a frequency swept modulation to the injection current of the DFB laser. The modulation applied to the laser may be gated on and off, as in the gated delayed self-homodyne technique, with a period equal to twice the differential time delay τ_0 of the interferometer [6]. The use of gated modulation is helpful in reducing the filtering effects of the interferometer. The lightwave signal analyzer tracks and measures the swept response of the first modulation sideband. From the swept sideband measurement, the FM deviation $\Delta\nu(f)$ as a function of modulation frequency is obtained.

For gated modulation, at a given instant of time, there will be mixing of the modulated field with an unmodulated field, the latter serving as a homodyne local oscillator. On the other hand, if gating is not used, the mixing will be between the modulated field and a delayed version of itself. The photocurrent spectrum for these two cases, dropping the intensity detection terms, is given as

$$Si(f) \approx \frac{\delta\upsilon/\pi}{(\delta\upsilon)^2+f^2} \otimes S'(f)$$

$$S'(f) = \begin{cases} S_m^g(f) & \text{gated modulation} \\ S_{m'm}(f) & \text{nongated modulation} \end{cases} \tag{1}$$

where $S_m^g(f)$ is the power spectrum of the gated electric field modulation, $S_{m'm}(f)$ is the power-spectral density of the

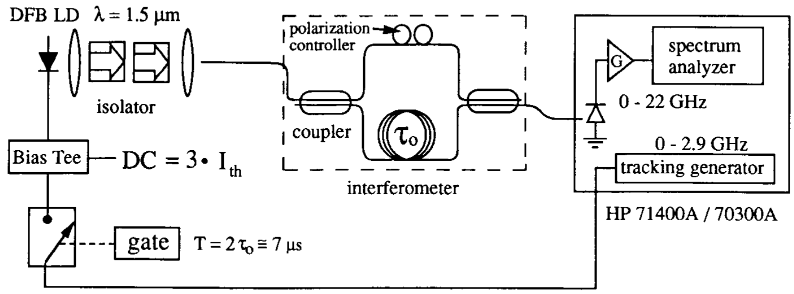


Fig. 1. Experimental setup for swept frequency deviation measurement of a DFB laser using S-GDSH technique, S-DSH is the same except the switch is bypassed.

product $m(t)$ and $m(t - \tau_0)$, $m(t)$ being the electric field modulation. $\otimes$ represents the convolution operator and $\delta\upsilon$ is the FWHM linewidth of the laser.

For small index FM modulation $J_1^2(\beta) = (\beta/2)^2$, with $\beta = \Delta\upsilon/f_S$, therefore the power spectrums, from (1) become

$$S_i(f) \approx \beta'^2 \frac{\delta\upsilon/\pi}{(\delta\upsilon)^2 + f^2} \otimes \delta(f - f_s)$$

$$\beta' = \begin{cases} \beta & \text{gated modulation} \\ \beta\sqrt{1 - \cos 2\pi f \tau_0} & \text{nongated modulation} \end{cases}. \quad (2)$$

As the modulation frequency f_s is swept, the analyzer tracks and measures the response at the frequency f_s, the Lorentzian co-factor in (2) thus remains constant, at its peak value, and the resulting measurement is proportional to β'^2. If the IF bandwidth of the signal analyzer is large compared to $1/\tau_0$, the cos $2\pi f \tau_0$ variation can be filtered out and the ungated technique will also yield a swept measurement proportional to β^2.

The swept $\Delta\upsilon(f)$ response is extracted from the swept β^2 measurement by multiplying by f^2, this can be performed (in log scaling) by subtracting the static Lorentzian characteristic (centered at zero frequency using the DSH technique for linewidth measurement) of the unmodulated laser when the measurement band of interest is well above the 3 dB linewidth $\delta\upsilon$ of the laser

$$S_i(f) \approx \frac{\delta\upsilon/\pi}{(\delta\upsilon)^2 + f^2} \propto \frac{1}{f^2} \qquad \text{if } f \gg \delta\upsilon. \quad (3)$$

Alternatively, the subtraction can be performed using an external instrument controller to load a waveform template into the signal analyzer trace memory, this increases the applicability of this technique to wider measurement frequency ranges.

The measured swept response characteristic is calibrated by making a power spectrum measurement using either the GDSH or Fabry–Perot techniques at a fixed modulation frequency and calculating the frequency deviation corresponding to the injection current modulation. Here, the injection current modulation was adjusted to null the first Bessel sideband $J_1^2(\beta)$, corresponding to a β of 3.84, yielding an FM efficiency of approximately 300 MHz/mA at 350 MHz for the DFB laser measured in the experiment.

III. Experiment

In the experiment, the tracking generator output power was ramped positively with frequency to insure a reasonable FM index across the measurement band. The ramped current modulation was normalized out of the final measurement by connecting the tracking generator output directly to the electrical input of the signal analyzer, storing the swept response and later subtracting it from the measurement of $\Delta\upsilon(f)$. This measurement corresponds to trace C in Fig. 2(a). The measurement of linewidth [see (3)] and swept β^2 [see (2)], correspond to traces B and A, respectively, in Fig. 2(a). The trace subtraction (A-B-C) was performed, yielding the swept deviation response proportional to $\Delta\upsilon(f)$ as shown by the solid curve in Fig. 2(b). The curve is relatively flat since the upper measurement frequency, for the tracking generator available, was below the relaxation resonance frequency of the laser biased at 3 I_{th}.

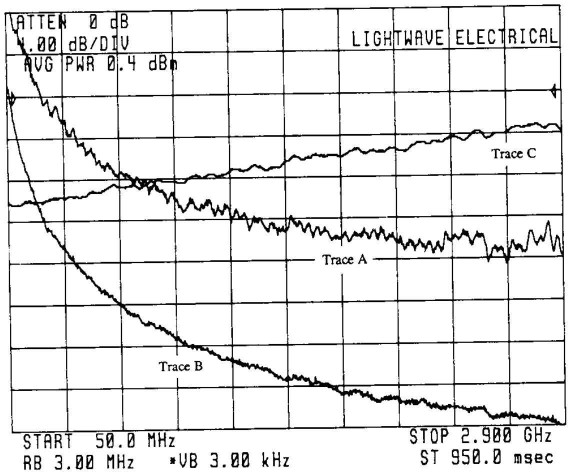
The individual points plotted in Fig. 2(b) were performed using the G-DSH technique for power spectrum measurement. The deviation was calculated at each measurement frequency from the relative heights of the power spectrum sidebands. The two techniques agree relatively well, the reference amplitude for the S-DSH technique was set to give the best match with the GDSH measurement. The lower frequency limit of the S-DSH technique was 100 MHz in this case in order to maintain the approximation in (3).

A comparison of the gated and nongated S-DSH techniques is shown in Fig. 3. Both techniques exhibit similar fast ripple but differ slightly at some frequencies. Differences may be due in part to slow thermally induced time varying external cavity effects on the DFB inducing variations in $\alpha_{\text{eff}}(\omega)$ and thus the FM efficiency.

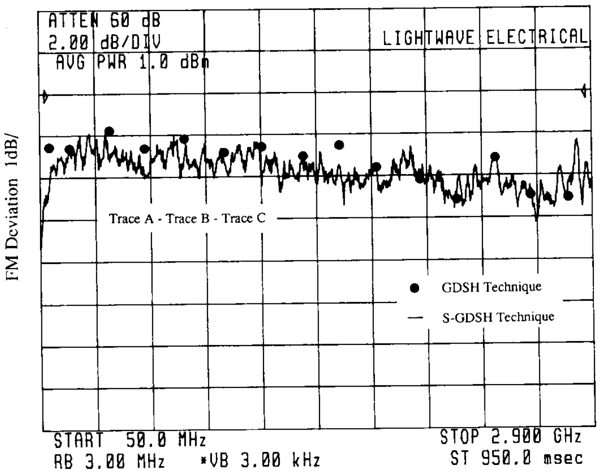
Additionally, as an intermediate experimental result, measurement of β suggests a way to estimate the frequency response of the effective amplitude-phase coupling factor, $\alpha_{\text{eff}}(2\pi f)$, of the laser using the relationship [7]

$$|\beta(f)/m_i(f)| = \alpha_{\text{eff}}/2 \sqrt{1 + \left(\frac{f_g}{f_s}\right)^2} \quad (4)$$

where $m_i(f)$ is the frequency swept optical intensity modulation index and f_g is the characteristic frequency as described in [7].



(a)



(b)

Fig. 2. (a) Analyzer traces for swept FM deviation of a DFB laser biased at 3 I_{th} operating at 1548 nm. Trace *A* is swept sideband measurement, trace *B* is laser linewidth. Trace *C* is the RF injection current modulation applied to the laser. (b) Solid curve is the result of trace subtraction in (a) yielding swept FM deviation response. Dotted points are deviation measurements obtained from power spectrum measurements using GDSH technique.

IV. Summary

A new technique has been introduced permitting swept measurement of the modulus of the FM deviation response of a DFB laser using incoherent interferometry. Accurate measurement requires verification that the measured response is free of optical intensity detection and that the FM spectrum dominates over the AM spectrum, which is often the case. Optical intensity detection is easily identified since it is independent of the state of polarizations of the combined fields in the interferometer. The relative amounts of power associated with the AM and FM field spectra depend on the magnitude of α_{eff}. Comparison of the swept deviation response with the swept intensity response, the latter performed without the interferometer, should permit evaluation of the frequency response of the effective amplitude-phase coupling factor $\alpha_{\text{eff}}(\omega)$. Swept FM deviation measurements have been demonstrated up to 2.9 GHz using an amplitude-corrected instrumentation receiver, tracking generator and interferometer. This technique should be useful for rapid characterization of single and multiple-electrode DFB or DBR lasers for application in high-speed FSK lightwave communications systems.

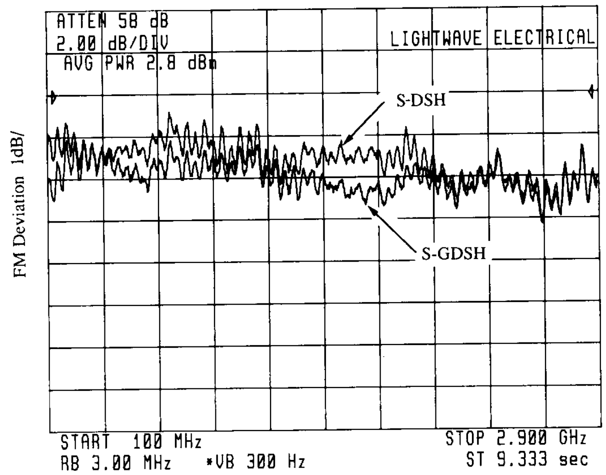


Fig. 3. Comparison of swept deviation response measurements performed by gated and nongated S-DSH techniques, measurements were performed sequentially.

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