Optical Feedback Effects Upon Laser Diode Oscillation Field Spectrum

FRANCOIS FAVRE, DANIEL LE GUEN, AND JEAN CLAUDE SIMON

Abstract—Optical feedback effects on spectral properties of a semiconductor laser diode coupled to a single-mode fiber cavity are investigated. Linewidth reduction from 6 MHz to less than 30 kHz and frequency stability improvement with increasing feedback are reported. Experiments are in good agreement with theory for short fiber cavities.

I. Introduction

THE possibility of coherent type single-mode fiber transmission systems has recently been reported [1]-[3]. The performances of these systems depend on the spectral purity and frequency stability of optical sources. For a single-mode laser operating far above the oscillation threshold, the theoretical minimum linewidth is determined by the random phase fluctuations. Due to the low Q value of a semiconductor laser cavity, the linewidth is not compatible with the requirements of coherent communication systems.

Spectral narrowing by optical feedback from a mirror or a grating has been reported [4]-[8]. Feedback effects were investigated for relatively short external cavities.

This paper reports experimental results on linewidth reduction and center frequency stabilization for a semiconductor laser coupled to a single-mode fiber whose output end has been carefully cleaved. A single-mode fiber cavity is insensitive to mechanical disturbances and easy to stabilize thermally. The overall dimensions of the external cavity can be reduced independently of the optical length. The power mode coupling efficiency between the laser diode and the fiber can be easily controlled experimentally. Measurements of the power feedback ratio, linewidth reduction, and satellite lines frequency separation for various external cavity lengths agree with the semiconductor laser feedback theory [9]. Our experimental results are in good agreement with theoretical predictions. Linewidth reduction from 6 MHz to less than 30 kHz has been obtained and center oscillation frequency stability greatly improved with feedback.

II. Experimental Setup

A. Laser Diode

The two lasers used in the experiments are AlGaAs CSP (Hitachi 1400) laser diodes coming from the same wafer. Their light versus current characteristics are almost identical. They oscillate on a single-mode near 820 nm and emit 8 mW per facet at 61 percent above threshold, which occurs at 74.5 mA and is practically unchanged in weak optical feedback conditions investigated in the following. The laser temperature is stabilized by a thermoelectric element.

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B. Single-Mode Fiber Cavity

The single-mode fiber cavity is end-butt coupled to the laser chip, the end of which oversteps the heat sink and is mounted on a three-axis piezoelectric translator. The output end of the single-mode fiber is carefully cleaved in order to obtain a reflecting interface orthogonal to the fiber axis.

The experimental setup used to control the fiber facet orthogonality is described in Fig. 1. A He-Ne laser beam is focused on the fiber facet and partially launched in the fiber mode. The distance separating a dot placed at the front focal point of the lens to its image formed on the same focal plane after reflection on the fiber facet is related to the local facet orthogonality. The orthogonality at the fiber core was found to be good to 1° and it is assumed in the following that the light power reflected back by the rear facet is entirely launched into the fiber backward mode.

The fiber is wound around a 30 mm diameter PZT ceramic in order to adjust the optical length of the cavity. Fiber and ceramic are immersed in oil and thermally stabilized by a thermoelectric element. The state of polarization (SOP) of the fiber output is analyzed through a polarizer. The fiber output SOP is maintained as linear as possible (with a cross polarized power ratio less than 5×10^{-3}) by monitoring the external cavity temperature. The light launched back into the laser mode is thus linearly polarized with the same SOP as that of the lasing mode whenever SOP changes along the fiber.

C. Spectral Measurements Method

A delayed self-heterodyne method is used to measure the laser linewidth [10]. The experimental arrangement is displayed in Fig. 2. The laser beam is launched in a two-wave interferometer consisting of a 3.9 km long single-mode fiber in one arm and an acoustooptic frequency shifter (71 MHz) in the other (a Faraday optical isolator avoids reflections from the interferometer). The two beams are then mixed in a short single-mode fiber and the photocurrent fluctuation spectrum is measured around the beat frequency with an RF spectrum analyzer. The photocurrent spectrum is directly related to the output intensity fluctuation spectrum $S(\Delta F)$ whose analytical expression is given in [11] as

$$S(\Delta F) = \frac{2}{\pi \Delta \nu} \exp(-2\pi \Delta \nu \tau_d) \cdot \left[\frac{\Delta F/\Delta \nu \sin(2\pi \Delta F \tau_d) + \sinh(2\pi \Delta \nu \tau_d)}{1 + (\Delta F/\Delta \nu)^2} - \frac{\sin(2\pi \Delta F \tau_d)}{\Delta F/\Delta \nu} \right] \quad (1)$$

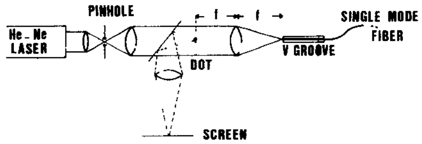

Fig. 1. Schematic of experimental arrangement used for measurements of fiber end orthogonality.

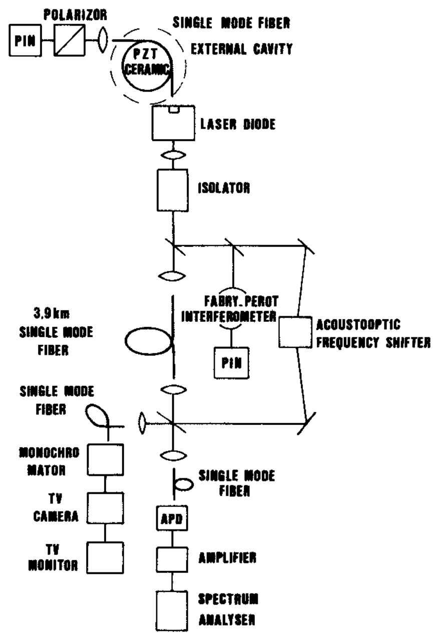

Fig. 2. Experimental setup used for linewidth and frequency fluctuations measurements on semiconductor laser coupled to external single-mode fiber cavity.

where τ_d is the delay time between the arms of the interferometer, $\Delta\nu$ is the oscillation field linewidth, and ΔF is the frequency deviation. The photocurrent spectrum is proportional to the autocorrelation function of the field spectrum as long as the linewidth $\Delta\nu$ is large compared to the interferometer resolution τ_d^{-1}. When $\Delta\nu \lesssim \tau_d^{-1}$, $\Delta\nu$ can be derived from the spectrum half width $\Delta F_{1/2}$ through a correction factor $\Delta F_{1/2}/\Delta\nu$ which is plotted in Fig. 3 against $2\pi\Delta\nu\tau_d$.

III. Oscillation Field Spectrum

A. *Theoretical Expressions*

An analytical expression of the oscillation field spectrum for a semiconductor laser with external mirror feedback has recently been proposed [9]

$$P(\Delta\nu) = \left\{1 + \left(\frac{2\Delta\nu}{\Delta\nu_{SL}}\right)^2 \left[\left(1 + X\frac{\sin 2\pi\Delta\nu\tau}{2\pi\Delta\nu\tau}\right)^2 + X^2\left(\frac{1-\cos 2\pi\Delta\nu\tau}{2\pi\Delta\nu\tau}\right)^2\right]^2\right\}^{-1} \tag{2}$$

where $\Delta\nu_{SL}$ is the full linewidth for the solitary laser, τ is the roundtrip time of the external cavity, and X is a feedback influence parameter given by

$$X = \gamma\sqrt{\eta}\,\tau. \tag{3}$$

η is the power feedback ratio, and γ is a coefficient derived from steady-state oscillation condition for a diode laser with external mirror [9], [12]

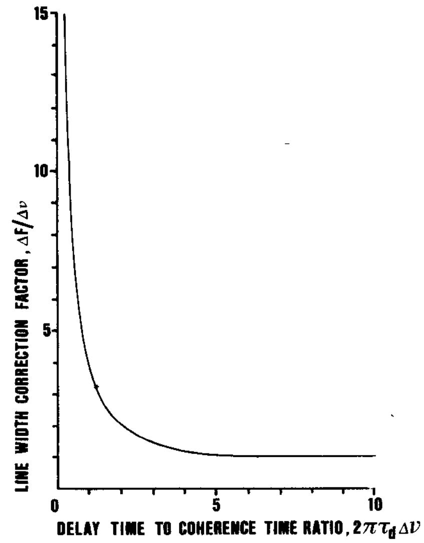

Fig. 3. Calculated photocurrent spectrum half width to laser linewidth ratio $\Delta F_{1/2}/\Delta\nu$ versus $2\pi\Delta\nu\tau_d$ where τ_d is the delay time between interferometer arms.

$$\gamma = \frac{c}{2n_D l_D} \tag{4}$$

where l_D is the laser diode length, n_D is the refractive index, and c is the light velocity.

Another expression for γ can be derived from a modified van der Pol equation and written as [7], [13], [14].

$$\gamma = \frac{c}{2n_D l_D}\left[\alpha_D l_D - \ln R_D\right] \tag{5}$$

where α_D is the free carrier absorption loss coefficient and R_D is the diode facet reflectivity. γ as given in (5) is equal to $(2\tau_p)^{-1}$, τ_p being the photon lifetime. A typical value for $\alpha_D - (1/l_D)\ln R_D$ is 45 cm^{-1} for a 300 μm long CSP laser diode [15] providing $\gamma = 135$ GHz from (5) against $\gamma = 100$ GHz from (4).

An expression of $\Delta\nu_{SL}$ can be derived from the modified Schawlow-Townes expression giving the linewidth of a solitary laser [16]

$$\Delta\nu_{SL} = \frac{h\nu}{8\pi P_o}\left(\frac{c}{n_D l_D}\right)^2 (\ln R_D - \alpha_D l_D)(\ln R_D)\, n_{sp} \tag{6}$$

where P_o is the single ended output power and n_{sp} is the spontaneous emission factor which lies in the 2.3-2.7 range at room temperature [16].

The oscillation field spectrum is narrowed with increasing the feedback influence parameter X as derived from (2) when in-phase condition is achieved (the emitted field and the returning field are then in phase on the laser end facet). In feedback condition, the linewidth is given by [7], [9]

$$\Delta\nu = \Delta\nu_{SL}(1 + X)^{-2}. \tag{7}$$

The oscillation field spectrum shows satellites which are enhanced and pushed to the external cavity mode frequency with increasing X. The normalized frequency deviation $\tau\delta\nu$ is calculated from (2) and plotted versus X in Fig. 4. The parameter X can be derived from measurements of $\tau\delta\nu$ using Fig. 4. The corresponding value for the linewidth reduction ratio can then be compared with the theoretical value given by (7).

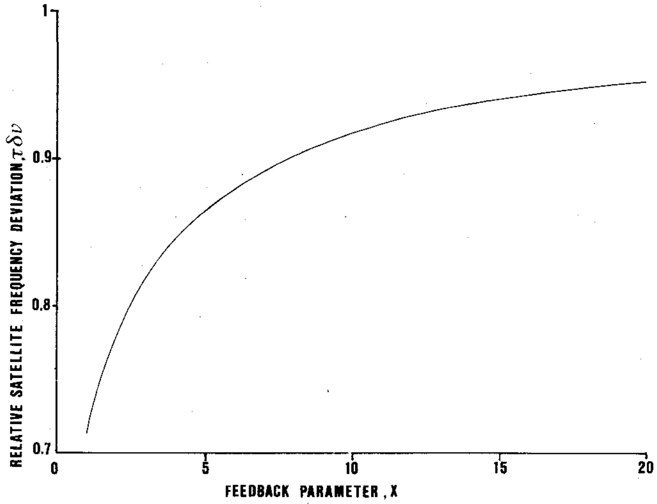

Fig. 4. Calculated normalized satellite line frequency deviation $\tau\delta\nu$ versus feedback parameter X. τ is the external cavity roundtrip time. The function $\tau\delta\nu(X)$ can be approximated by $X/(X+1)$ for $X > 20$.

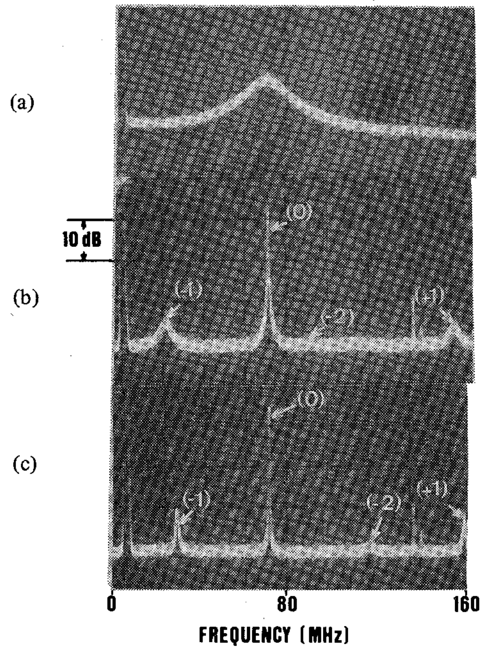

Fig. 5. Photocurrent fluctuations spectrum with increasing feedback from a 1.027 m long single-mode fiber. Photovoltage output V is proportional to fiber output light power. (a) $V = 0$ (solitary laser diode), (b) $V = 4$ mV, (c) $V = 10$ mV, $I/I_{th} = 1.61$. (b) and (c) show satellite lines due to feedback and labeled (+1), (−1), (−2). (−1) and (−2) lines are displayed in negative frequency domain. Spectrum analyzer bandwidth: 300 kHz.

B. Experimental Results

1) Power Feedback Ratio: The power feedback ratio η is defined as the relative power returning into the laser diode mode and given by [9], [12]

$$\eta = \rho^2 (1 - R_D)^2 R_D^{-1} (1 - R_F)^2 R_F \exp(-2\alpha_F L_F) \tag{8}$$

where R_F is the mode power reflectivity of the fiber output end, α_L is the propagation loss coefficient due to absorption and curvatures, L_F is the fiber length, and ρ is the power mode coupling efficiency between the laser diode and the fiber. η can be related to the feedback fiber output by

$$\eta = (1 - R_D)^2 R_D^{-1} (1 - R_F)^{-2} R_F V_D^{-2} V^2 \tag{9}$$

where V and V_D are photovoltages respectively proportional to the fiber output power and to the laser diode output power. It should be pointed out that propagation losses are taken into account in (9). Measurements give $V_D = 220$ mV at $I = 1.61 I_{th}$ and calculated values for R_D and R_F are, respectively, 0.32 and 0.035. In the following, linewidth measurements are performed for decreasing roundtrip time values by shortening the fiber while the output end is kept unchanged.

2) Satellite Lines Frequency Separation: An example of photocurrent fluctuations spectrum alteration with feedback is shown in Fig. 5. The frequency separation $\delta\nu$ between lines is measured as a function of the fiber output V for various external cavity lengths. The feedback parameter X is then derived from its theoretical dependence of $\tau\delta\nu$ given in Fig. 4; results are depicted in Fig. 6 as a function of the fiber output photovoltage V for different values of the external cavity roundtrip time τ. Each straight line is a least square fit to the data. The mean value of X/V obtained from Fig. 6 as a function of τ is shown in Fig. 7. The solid line represents the linear law derived from (3) and (9) and given by

$$\frac{X}{V} = (1 - R_D) R_D^{-1} (1 - R_F)^{-1} R_F V_D^{-1} \gamma\tau \tag{10}$$

with $\gamma = 135$ GHz as given by (5). Experimental points deviate from the linear law with increasing τ.

3) Linewidth Reduction Ratio: The linewidth reduction ratio $\Delta\nu/\Delta\nu_{SL}$ is measured as a function of the output fiber photovoltage V and displayed in Fig. 8 versus the corresponding X values derived from Fig. 6. The minimum value for $\Delta\nu$ is obtained by monitoring the fiber optical length to achieve in-phase condition. Experimental points are in good agreement with the theory except for $\tau = 10$ ns.

4) Frequency Stability: Fig. 9 shows the output of a low finesse scanned Fabry–Perot interferometer (free spectral range: 940 MHz; resolution: 135 MHz). Short term frequency stability is improved with increasing X. External cavity mode jumping can be observed during the time exposure of 5 s for low X values. Oscillograms are also made using a 4 MHz resolution Fabry–Perot interferometer (FSR: 300 MHz) and shown in Fig. 10. Center frequency fluctuations are estimated to lie in the ±2 MHz range during 5 s in feedback condition. Using a 15 GHz FSR Fabry–Perot interferometer with a finesse of 18, it has not been possible to observe self-pulsing phenomena as previously reported in similar conditions [17].

5) Linewidth Versus Laser Output Power Dependence: The linewidth has been measured as a function of the normalized bias current for solitary lasers and with feedback influence. Experimental results are shown in Fig. 11. A theoretical linewidth of 200 kHz at $I = 1.61 I_{th}$ (corresponding to $P_o = 8$ mW) is derived from the modified Schawlow-Townes expression (6) while the measured value is 30 times greater. A factor of 20 between experimental and theoretical values has previously been reported [16]. The enhanced linewidth is attributed to the variation of the real refractive index with carrier density [18].

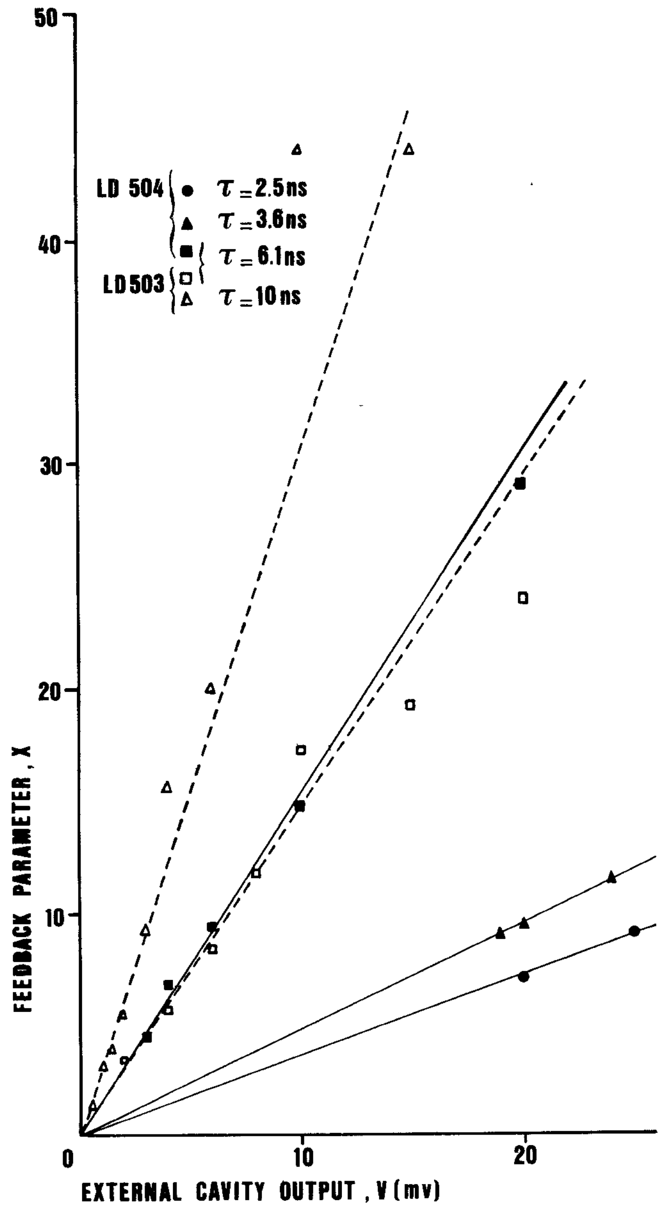

Fig. 6. Feedback parameter X as a function of fiber output V for various fiber cavity lengths. X is derived from line frequency separation through the theoretical law displayed in Fig. 4. Each straight line is a least square fit to the data. Two laser diodes are used: LD 504 (solid lines); and LD 503 (dashed lines). $I/I_{th} = 1.61$.

6) Feedback Effects Due to the Front Facet of the Fiber: Cyclic laser diode mode jumping is observed when the external fiber cavity is continuously moved away from the laser diode. It can be explained considering the frequency selectivity arising from the three-mirror laser cavity consisting of the laser diode of optical length L and the fiber input facet at a distance d. Let us consider the cavities of lengths L and $L + d$ as shown in Fig. 12(a). Assume the laser matching occurs for the mth mode of the laser cavity [Fig. 12(b)] and for the nth mode of the longest cavity [Fig. 12(c)], these modes being on the high frequency side with regard to the gain spectrum peak. Frequency mismatching between mth and nth modes develops with increasing d while it decreases between $(m - 1)$th and $(n - 1)$th modes until the laser frequency jumps to the $(m - 1)$th modes. Mode jumps will be repeated until frequency

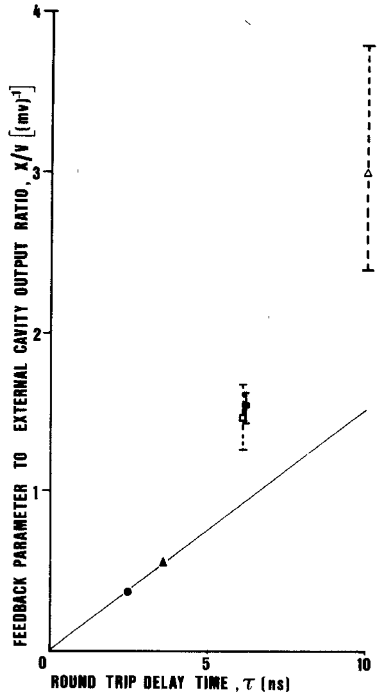

Fig. 7. Mean values of X/V obtained from Fig. 6 as a function of roundtrip time τ. Solid line is the calculated result (relation (10) with γ = 135 GHz).

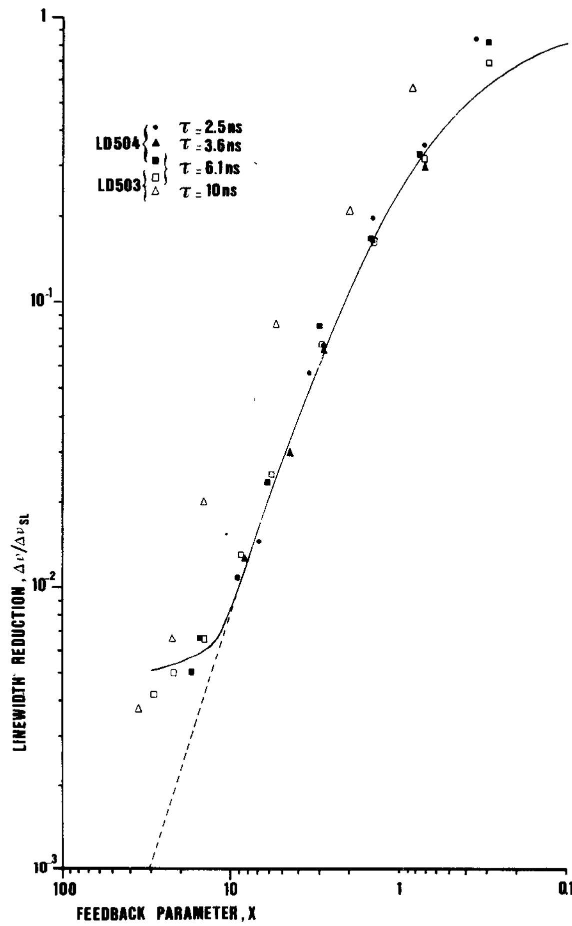

Fig. 8. Linewidth reduction ratio $\Delta\nu/\Delta\nu_{SL}$ versus feedback parameter X. Dashed line is the plot of $(1 + X)^{-2}$. Solid line is the theoretical linewidth reduction ratio when measurements are achieved using the two beams interferometer with a delay time τ_d = 19 μs.

(a)

(b)

(c)

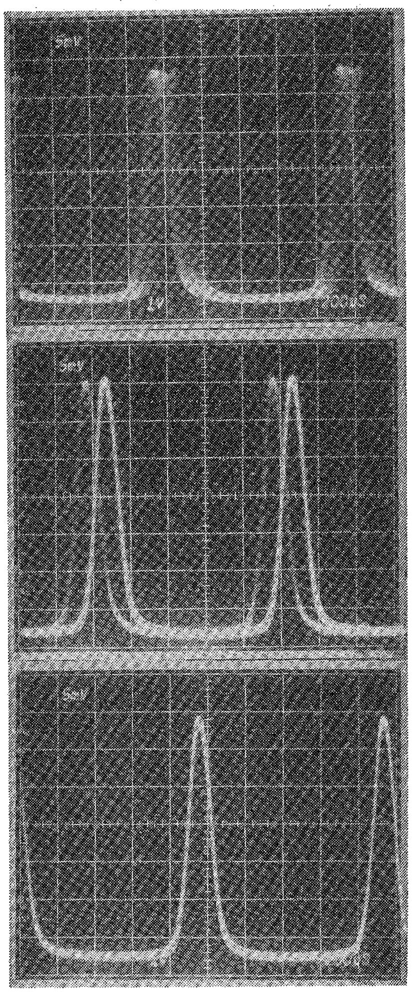

Fig. 9. Linearly scanned Fabry–Perot interferometer output with increasing feedback (a) $X = 0$ (solitary laser), (b) $X = 10$, (c) $X = 25$. $\tau = 10$ ns, FSR = 940 MHz, resolution = 135 MHz. Oscillograms are the superposition of 2500 scans corresponding to a time exposure of 5 s. $I/I_{th} = 1.61$.

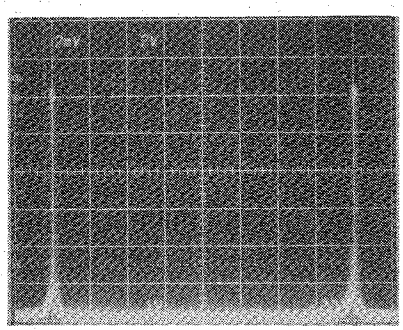

Fig. 10. Interferometric analysis of laser diode in feedback conditions given in Fig. 9(c). FSR = 300 MHz, resolution = 4 MHz, exposure time is 5 s.

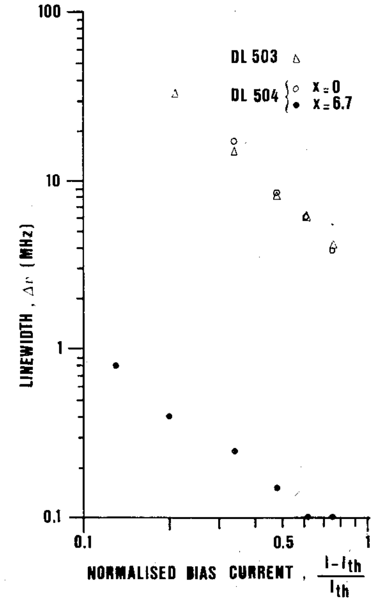

Fig. 11. Linewidth measurements as a function of normalized bias current in solitary and feedback conditions ($\tau = 2.5$ ns, $X = 6.7$).

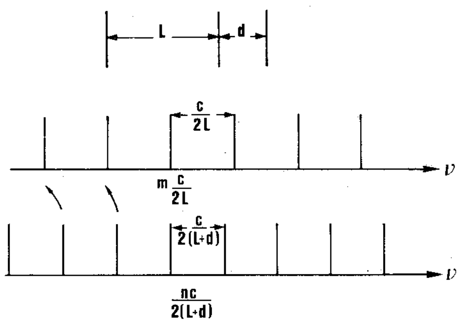

Fig. 12. Schematic of modes of the three-mirror cavity.

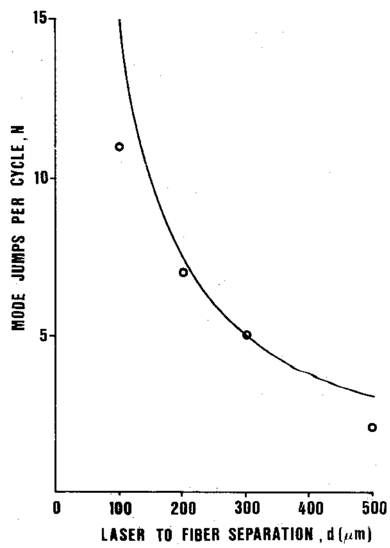

Fig. 13. Number N of mode jumps per cycle as a function of d. Solid line corresponds to theoretical predictions.

matching occurs between mth and $(n+1)$th modes. The number of jumps per cycle is approximately given by

$$N \approx \frac{L}{d}. \tag{11}$$

Experimental determination of N is reported in Fig. 13 and compared to the theoretical expression (11). Effects upon the linewidth remain negligible due to low values of the cavity length and of the feedback ratio (provided $d \geqslant 100$ μm). These results have been confirmed by using a silica plate in the position of the fiber input face.

IV. Conclusion

Optical feedback effects upon spectral properties of semiconductor lasers have been investigated. Linewidth reduction from 6 MHz to less than 30 kHz has been obtained for a single-mode semiconductor laser diode coupled to a single-mode fiber whose output end is cleaved. Experimental results are in good agreement with theory for fiber length below 50 cm. The use of a single-mode fiber makes the external cavity insensitive to mechanical disturbances and overall dimensions can be easily reduced. These features associated with the high spectral purity make this optical source compatible with the requirements of coherent communication systems.

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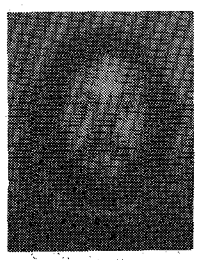

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