15-GHz Modulation Bandwidth, Ultralow-Chirp 1.55-μm Directly Modulated Hybrid Distributed Bragg Reflector (HDBR) Laser Source

R. Paoletti, *Member, IEEE,* M. Meliga, *Member, IEEE,* G. Rossi, *Student Member, IEEE,* M. Scofet, and L. Tallone

***Abstract*—A hybrid source has been realized, integrating a fast Fabry–Perot laser and a fiber grating. The device has shown very good performances in the 1530–1570-nm range, obtaining 16 mA of threshold current at 20 °C, 1.6-mW fiber optical power and 48 dB of sidemode suppression ratio at 50 mA bias current. The cavity length was designed to achieve a good tradeoff between chirp reduction and increasing speed. The device has shown for the first time, to our knowledge, more than 15 GHz of small-signal modulation bandwidth, and 10-Gb/s modulation capability. Moreover, a penalty-free transmission experiment at 2.5 Gb/s over 100 km of standard fiber has confirmed the very low wavelength chirp of the device. These previous characteristics together with an extremely low temperature dependence (<0.02 nm/°C) make the hybrid distributed Bragg reflector (HDBR) particularly suitable for dense wavelength-division-multiplexing systems.**

***Index Terms*— Gratings, high-speed devices, quantum-well lasers, semiconductor lasers, wavelength-division multiplexing.**

I. Introduction

SEVERAL realizations of hybrid distributed Bragg reflector (HDBR) have been reported in literature, suitable for different applications as pump laser [1], low-cost source for optical access network [2], or wide frequency range pulse generator [3]. All those devices have been realized by integrating an antireflection coated Fabry–Perot (FP) laser with an external cavity, obtained by a grating photo-induced on a fiber coupled to the laser. In the realization reported in [2], the alignment tolerances between laser and fiber have been successfully reduced, by using a spotsize converter (SSC) laser coupled into a cleaved fiber. Recently, a four-channel multiwavelength fiber grating source has been reported [4], and a transmission experiment at 2.5 Gb/s over 300 km of standard fiber has been demonstrated [5].

For the first time, to our knowledge, using a fast Fabry–Perot laser [6] and an optical cavity properly designed, we demonstrate 10 Gb/s of direct modulation. Main characteristics of our device are a small-signal bandwidth in excess of 15 GHz, a line width less than 40 kHz at the maximum output power, and a sidemode suppression ratio (SMSR) of 48 dB. With respect to a similar distributed-feedback (DFB) laser, we obtained a strong reduction of the wavelength chirp (less than 10 MHz/mA at 1 MHz of small-signal modulation) and of the temperature dependence (less than 0.02 nm/°C), in both case one order of magnitude better than with respect to the DFB laser. The chirp reduction has also been demonstrated by means of a 2.5 Gbit/s transmission experiment through 100 km of standard (NDS) fiber, showing a negligible power penalty (0.2 dB). This hybrid laser is therefore, suitable for operation as a source for high speed dense wavelength-division-multiplexing (WDM) system applications.

Manuscript received July 23, 1998; revised August 14, 1998.

R. Paoletti, M. Meliga, M. Scofet, and L. Tallone are with CSELT Centro Studi e Laboratori Telecomunicazioni S.p.A., 10148 Torino, Italy.

G. Rossi is with the University of Pavia, Department of Electronix, 27100 Pavia, Italy.

Publisher Item Identifier S 1041-1135(98)08788-6.

II. Device Structure

The hybrid distributed Bragg reflector was based on a fast (15-GHz small-signal bandwidth) FP laser diode, with an antireflection coating (AR) on the output facet (10^{-4} of residual reflectivity). The laser was a semi-insulating buried heterostructure (SI-BH), with a 1.55-μm InGaAsP MQW active layer, made by nine (80 Å thick) compressive strained (+0.9%) wells and eight (90 Å thick) tensile strained (−0.5%) barriers, grown by metal–organic chemical vapor deposition (MOCVD). Before the antireflective (AR) coating, the device exhibited 8 mA of threshold current; after the AR coating the threshold current was increased (to more than 25 mA), and the quantum efficiency was increased as well, obtaining more than 13 mW at 80 mA bias current.

The output beam was coupled into a standard single-mode fiber, with a UV grating centered at 1551 nm, featuring a reflectivity of 70%, and a bandwidth (full width half of maximum, FWHM) of 0.2 nm. The grating was about 10 mm long, and was located less than 2 mm from the fiber edge. In order to improve the coupling efficiency the fiber was tapered, and the residual cavity effects were eliminated by an antireflection coating on the taper itself. So far, the properties of the HDBR source have been fully demonstrated only on an optical bench; by using microwave probes, static measurements have been performed, showing good static behavior and reliability. A high-speed module is currently being developed, with the aim of obtaining both high-speed and good static characteristics.

To obtain a fast hybrid device a very short output cavity was designed. Defining τ_t the round-trip time of the external cavity laser, the resonance frequency can be evaluated by

$$f_r \approx 1/\tau_t = \frac{c}{2\left(\overline{n}_a L_a + \overline{n}_f L_{\text{eff}}\right)} \qquad (1)$$

where c is the vacuum speed of light, $\overline{n}_a$ is the laser effective index, L_a is the laser length, $\overline{n}_f$ is the fiber effective index,

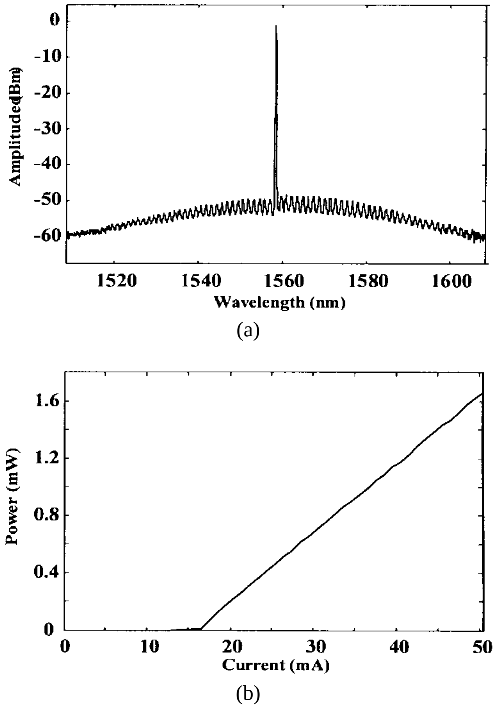


Fig. 1. (a) Optical spectrum of the HDBR, at 50 mA of bias current, with 48 dB of SMSR. (b) P–I device characteristic at 20 °C: a threshold current of 16 mA has been obtained, with a optical power into the fiber of more than 1.6 mW.

and $L_{\rm eff}$ the effective length of the external cavity, obtained by using the *effective mirror model* approximation reported in [7]. In (1), we have neglected the air path of the optical beam between the laser facet and the fiber lens (about 30 μm). By using (1), substituting the parameter values of our device, we have obtained a resonance frequency close to 14 GHz, showing therefore, a bandwidth wide enough for the 10-Gb/s operation. A different approach should be taken if the main goal is the reduction of the wavelength chirp, suggesting the use of a long external cavity. At the same time a long cavity requires a narrower FWHM of the grating, to maintain the single-mode operation. In general terms, a tradeoff between reduced chirp and wide bandwidth is necessary, depending on the system requirements. In our design, as it will shown later, we have considered the chirp reduction obtained with our cavity design large enough for 2.5-Gb/s transmission experiments.

III. Experimental Results

A. Static Characteristics

Threshold current of 16 mA at 20°C was achieved for the HDBR. Fig. 1(b) shows the power versus current (P–I) characteristic at the fiber output, with a very good linearity and without any power kink. The optical spectrum is also reported in Fig. 1(a), showing a SMSR of 48 dB. Key feature of this realization is that it can ensure similar SMSR in the 1530–1570-nm wavelength range, simply varying the center wavelength of the fiber grating. The operative temperature range was about 10 °C (16 °C–26 °C) and the temperature stability was better than 0.02 nm/°C.

By a self-homodyne measurement technique a line width of 40 kHz was obtained: however, this value was overestimated because it represents the resolution of the measurement setup. Different techniques are being currently tested in order to measure the true line width.

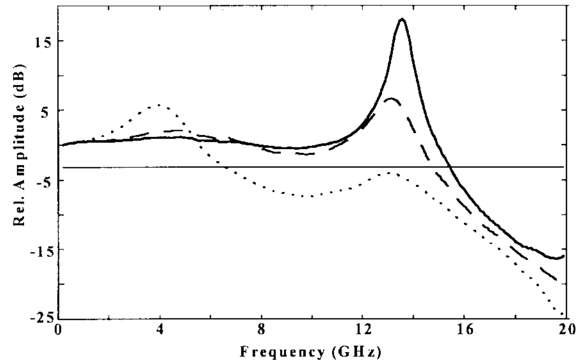
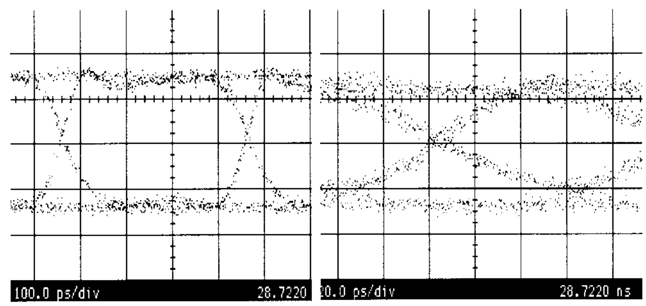


Fig. 2. Small-signal modulation bandwidth of the HDBR device, at 20 mA (• • •), 40 mA (- - -), and 60 mA (———) of bias current; the comparison shows the resonant effect of the external cavity, close to 14 GHz.



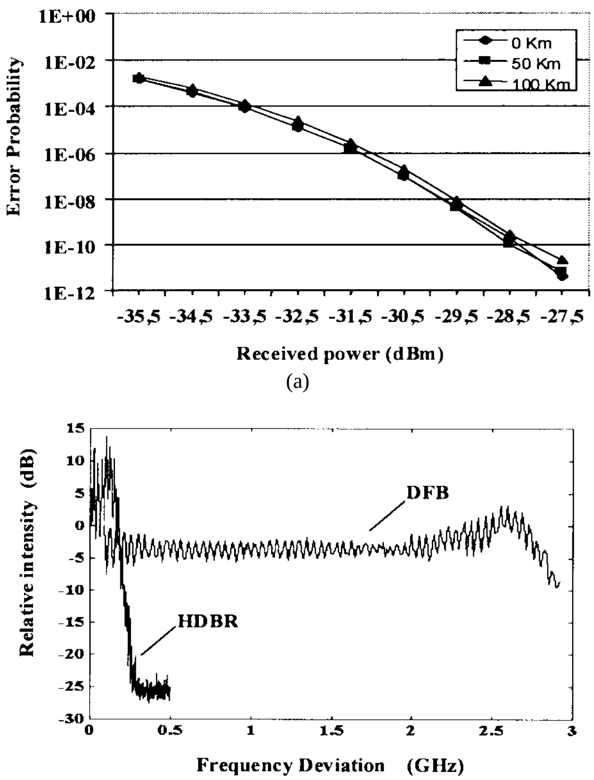
(a) (b)

Fig. 3. (a) 2.5 Gb/s and (b) 10-Gb/s eye pattern, with a 40-mA bias current and about 40-mA peak-to-peak digital signal; extintion ratios of 6–8 dB have been generally obtained, depending on the operating temperature.

B. Dynamic Characteristics

The small-signal modulation bandwidth has been investigated, in order to check the correct choice of the cavity length. The device was tested with a 40-GHz radio-frequency probe, especially designed for our chip. The modulation bandwidth of the HDBR device (with the feedback effect of the external cavity) is reported in Fig. 2, and indicates the wide bandwidth obtained (more than 15 GHz at 80 mA bias current). The strong peak is due to the external cavity resonance, close to 14 GHz in good agreement with the previous calculation. The combined effect of the laser's bandwidth and the external cavity resonance determines the large modulation bandwidth of the hybrid device.

As reported in [8], a strong resonance peak in the device's transfer function could affect the eye diagram in a digital transmission. To investigate the device response at large signal stimulus, we have therefore, tested the HDBR at different bit rates, biasing the device close to 30 mA and adding a modulation signal up to 40 mA peak-to-peak. Fig. 3 shows the 2.5- and 10-Gb/s eye patterns, obtained detecting the optical output directly with an HP 11982A 15-GHz lightwave converter, and analyzing the signal with a sampling oscilloscope (Tektronix 7704, with a 25-ps sample unit). A limited distortion is present in both eye diagrams, and therefore, the device can be used for bit rates up to 10 Gb/s.



(a) (b)

Fig. 4. comparison of the wavelength chirp measured on a standard DFB laser, with a sinusoidal modulation current (1 MHz) of 10-mA peak-to-peak, and a HDBR laser source, at 27-mA peak-to-peak of modulation current. The modulation index of the HDBR measurement has been intentionally increased in the comparison, to show the small line width broadening in the HDBR source.

An important feature of the external cavity laser is the reduction of the wavelength chirp. This reduction is a function of the round trip time in the external cavity τ_{ext} [9], [10]; the wavelength chirp of the HDBR device has been evaluated by *a gated-delayed self-homodyne technique* to test the chirp reduction introduced by the external cavity. We have measured the source spectrum broadening introduced by a low-frequency sinusoidal modulation in the 300-kHz to 30-MHz range, and we have obtained a chirp of less than 10 MHz/mA, extremely good compared to the value of 250 MHz/mA measured on a DFB source having the same structure and the same active layer. The comparison of the two spectrum, broadened by the small-signal modulation, is reported in Fig. 4. Further measurements will investigate the chirp at higher frequency range, as well as the transient wavelength chirp shown during the digital modulation.

We have tested the HDBR over 100 km of standard SMR fiber, with a 2.5-Gb/s direct modulation, using a commercial receiver. Bit-error rates (BER's) better than 10^{-12} have been obtained, with less than 0.2 dB power penalty at 10^{-9} BER (see Fig. 5), indicating the small-wavelength chirp of the device.

IV. CONCLUSION

15-GHz small-signal modulation bandwidth and digital transmission up to 10 Gb/s have been obtained with a hybrid laser made by using a fast Fabry–Perot laser and a properly

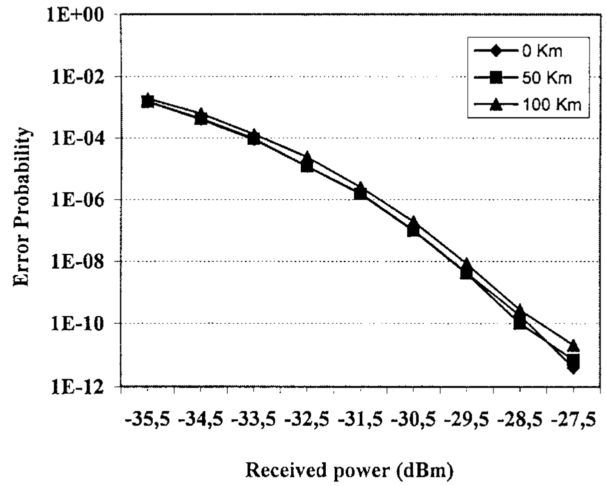


Fig. 5. BER curves for different fiber length (back-to-back, 50 and 100 km) at 2.5 Gb/s (@ 35-mA bias current, 40-mA peak-to-peak modulation signal).

designed_fiber grating external cavity. Transmission over 100 km of standard fiber at 2.5 Gb/s, with an extremely low sensitivity degradation, has been possible thanks to the strong reduction of the wavelength chirp. This device is therefore, suitable for long-distance application at high bit rates without external modulator.

ACKNOWLEDGMENT

The authors are very grateful to P. Gambini and M. Puleo for fruitful discussion about system measurements and applications. They would also like to thank D. Bertone, R. Fang, and G. Morello for the Fabry–Perot laser realization and C. Coriasso and D. Re for antireflection coatings.

REFERENCES

[1] A. Hamakawa, T. Kato, G. Sasaki, and M. Shigehara, "Wavelength stabilization of 1.48 μm pump laser by fiber grating," in *ECOC 1996,* Oslo, Norway, pp. 119–122, paper MoC 3.6.

[2] R. Zengerle, H. Burkhard, R. Ries, B. Hübner, C. Gréus, and E. Kuphal, "Large-spot diodes with stable carrier frequency by an external fiber grating," in *IPR 1996,* Boston, MA, pp. 649–652, paper IThD3-1.

[3] P. A. Morton, V. Mizrahi, P. A. Andrekson, T. Tanbun-Ek, R. A. Logan, P. Lemaire, D. L. Coblentz, A. M. Sergent, K. W. Wecht, and P. F. Sciortino, Jr., "Mode-locked hybrid soliton pulse source with extremely wide operating frequency range," *IEEE Photon. Technol. Lett.,* vol. 5, pp. 28–31, Jan. 1993.

[4] A. Hamakawa, T. Kato, G. Sasaki, and M. Shigehara, "A four-channel multiwavelength fiber-grating external-cavity laser array," in *OFC Tech. Dig.,* Dallas, TX, 1996, p. 297, paper ThM3.

[5] F. N. Timofeev, P. Bayvel, V. Mikhailov, P. Gambini, R. Wyatt, R. Kashyap, M. Robertson, R. J. Campbell, and J. E. Midwinter, "Low-chirp, 2.5 Gbit/s directly modulated fiber grating laser for WDM networks," in *OFC Tech. Dig.,* Dallas TX, 1996, p. 296, paper ThM1.

[6] R. Paoletti, D. Bertone, A. Bricconi, R. Fang, L. Greborio, G. Magnetti, and M. Meliga, "Comparison of optical and electrical modulation bandwidths in three different 1.55 μm InGaAsP buried laser structures," in *Photonics West 96, Functional Photonic and Fiber Devices,* San Jose, CA, 1996, pp. 296–305, paper 2695.

[7] L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Integrated Circuits.* New York: Wiley, 1995, ch. 3, pp. 65–108.

[8] T. Hayashi, K. Katsura, and H. Tsunetsugu, "New hybrid integrated laser diode-drivers using microsolder bump bonding: SPICE simulation of high-speed modulation characteristics," *J. Lightwave Technol.,* vol. 12, pp. 1963–1970, Nov. 1994.

[9] K. Petermann, *Laser Diode Modulation and Noise.* Dordrecht, The Netherlands: Kluwer Academic, 1988, ch. 4, pp. 250–271.

[10] N. A. Olsson, C. H. Henry, R. F. Kazarinov, H. J. Lee, and B. H. Johnson, "Relation between chirp and linewidth reduction in external Bragg reflector semiconductor laser," *Appl. Phys. Lett.,* vol. 51, no. 2, pp. 92–93, July 13, 1987.