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# Highly Coherent Electronically Tunable Waveguide Extended Cavity Diode Laser

**V. Crozatier[1], G. Gorju[1], F. Bretenaker[1], J.-L. Le Gouët[1], I. Lorgeré[1], B. Krishna Das[2], and W. Sohler[2]**
*[1]Laboratoire Aimé Cotton, CNRS, Bâtiment 505, Campus universitaire, 91405 Orsay CEDEX, France*
*[2]Angewandte Physik, Universität-GH Paderborn, 33098 Paderborn, Germany*
*Author e-mail address: vincent.crozatier@lac.u-psud.fr*

**Abstract:** We introduce a frequency agile extended cavity diode laser using an integrated Bragg reflector in a Ti:Fe:LiNbO$_3$ waveguide, emitting in the 1.5-µm telecommunication window. Improved stability and efficient electro-optic frequency control are achieved.

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## 1. Introduction

Highly coherent lasers emitting a stable frequency and capable of fast tunability are required for several applications, for instance coherent transmission systems, LIDAR detection, and RF signal processing. Semiconductor-based architectures have been proposed and demonstrated to meet all these requirements. DFB and DBR structures are very compact, but their emission linewidth usually lies in the MHz-range, and their tunability is neither linear nor reproducible due to the interplay of electrical and thermal effects. Extended cavity diode lasers provide both good spectral purity and tunability. More precisely, fast scans over tens of GHz have been achieved by electrical means, including intra-cavity electro-optical (EO) crystals [1]. However, high voltages are needed to provide such sweeps, which limits both tuning range and speed. Moreover, the different elements constituting the cavity make it very sensitive to external perturbations, hence degrading laser stability.

These laser key-characteristics can be improved using waveguide structures. First, one can integrate an EO phase section and a Bragg grating in a single device. Second, the reduction of the spot size in the cavity from 1 mm (typical in a bulk cavity) to a 10-µm guided mode reduces by two orders of magnitude the voltage needed for frequency tuning. Indeed the EO tuning response varies as the inverse of the electrodes spacing, limited by the beam size. Such an integrated cavity has been proposed in a KTP substrate [2], but no real improvement in the EO tuning was performed. We here demonstrate a waveguide extended cavity diode laser (WECDL) in a LiNbO$_3$ substrate working at 1.5 µm, with a high intrinsic stability and a high EO tuning slope.

## 2. Laser cavity and typical characteristics

The cavity is sketched in Fig. 1(a). The active medium is a HR/AR-coated laser diode delivering up to 75 mW of amplified spontaneous emission with a 75-mA current. The diode light is coupled into the waveguide using an AR-coated aspheric lens. Different waveguide structures delineated along the Z-axis are fabricated by indiffusion of photolithographically defined 100-nm thick Ti-stripes into the surface of a X-cut LiNbO$_3$ crystal. The resulting waveguides are either 14-µm (two mode guiding) or 7-µm (single-mode guiding) wide. The substrate is 4.8-cm long, 1-mm thick, with end faces polished under an angle of 5.8°. The input face is AR-coated. A 13-mm long Bragg grating is engraved in a Fe-doped section of the waveguide by a holographic set-up with an argon laser, exploiting the photorefractive effect. The grating is thermally fixed [3] and later refreshed with blue light homogeneous illumination, e.g., by using GaN LEDs. Fig. 2(c) shows a typical transmission spectrum of a Bragg grating.

Up to 60% of the diode light can be coupled in both single- and multi-mode waveguides, which have propagation losses between 0.1 and 0.2 dB/cm. A Bragg reflectivity of 20 % and a diode current of 75 mA yield a 7-mW optical output power of the WEDCL at $\lambda$ = 1553.75 nm (see Fig.1(c)). The polarization is linear along the Y axis (TE mode), with a contrast of 30 dB. Single frequency oscillation in a single spatial mode is obtained in the 14-µm wide guides when the fundamental mode only is excited. In single-mode guides, the laser emission is single frequency at low current, then turns to longitudinally multi-mode emission at higher currents, and finally coherence collapse occurs. The reason for this observation remains unknown yet. The following spectral characterization is performed in a 14-µm guide.

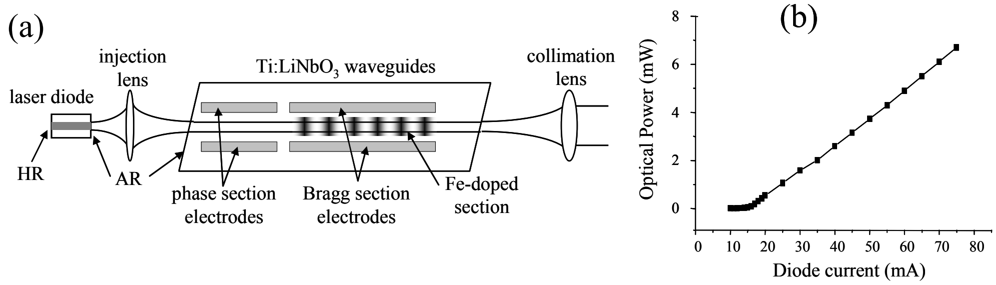

Fig. 1. (a) Laser architecture; (b) Laser output power vs diode current.

## 2. Spectral performances

When the laser operation is single frequency, we measure a side mode suppression ratio better than 40 dB using a Fabry Perot interferometer. The suppression of the diode spontaneous emission is measured to be 50 dB, with an optical spectrum analyzer. The coherence time of the laser evolves linearly with the output power, reaching 18 µs at 7 mW, which corresponds to a linewidth of 18 kHz. As can be seen in Fig 2(a), the laser stability on short timescales obeys a quasi-1/f noise spectrum on a 100 kHz bandwidth only. The standard deviation associated to the power spectral density of Fig. 2(a) is 16 kHz in a 10 kHz to 100 kHz integration bandwidth. As for long term stability, the laser wavelength drifts within +/- 1 pm (limited by the precision of our wavemeter) during several hours without any external stabilization. In comparison with a bulk cavity, the intrinsic stability of this WECDL architecture is clearly improved with thanks to integration and the Bragg grating stability.

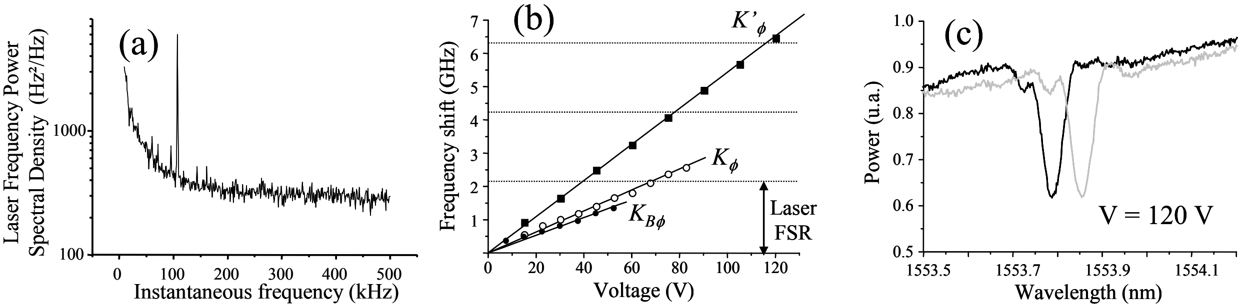

Fig 2. (a) Laser frequency power spectral density; (b) EO tuning of the Bragg phase response (filled circles), the phase section (empty circles) and both sections (squares); (c) Bragg grating spectral displacement with and without applied voltage.

Finally, we test the frequency agility of the WEDCL. Two sets of electrodes are implemented on the substrate in order to shift the cavity optical length, and the Bragg wavelength (see Fig. 1(a)). The phase section exhibits an EO tuning slope $K_\phi = 32$ MHz/V, with continuous tuning over one cavity free spectral range (see empty circles in Fig. 2(b)). The Bragg wavelength moves with a scale factor $K_B = 69$ MHz/V (see Fig. 2(c)). As the grating is engraved in the propagation direction, the Bragg section also exhibits a phase response $K_{B\phi} = 22$ MHz/V (see filled circles in Fig. 2(b)). When one applies the same voltage on both Bragg and phase electrodes, the laser EO slope is $K'_\phi = 55$ MHz/V (see squares in Fig. 2(b)). One can achieve 6.6 GHz-wide frequency scans without mode-hop, and very fast chirp capability up to 5.5 GHz in 5 µs have been demonstrated. Although not optimized, the scale factor $K'_\phi$ is already larger than previously reported values [1,2]. It can be increased by a factor of 5 using the $r_{33}$ EO coefficient (30 pm/V), as we here use the $r_{22}$ coefficient (6 pm/V). Other techniques of Bragg grating engraving can be implemented (surface relief [4], proton exchange [5]). We believe this laser corresponds to an ideal source for many applications.

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