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# **Continuous-wave single-frequency operation of Fabry-Perot laser diodes by self-injection phase locking using feedback from a fiber Bragg grating**

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## **Abstract**

Single-frequency operation of uncoated Fabry-Perot laser diodes is demonstrated by phase-locking the laser oscillations through self-injection seeding with feedback from a fiber Bragg grating. By precisely tuning the laser temperature so that an axial-mode coincides with the short-wavelength band edge of the grating, the phase of the feedback is made conjugate to that of the axial mode, locking the phase of the laser oscillations to that mode.

## 1. Introduction

Because the gain-bandwidth of Fabry-Perot diode lasers is very broad relative to the axial mode spacing, the laser oscillations cannot stabilize at one (single-frequency) mode, and hop rapidly between modes. This instability has been circumvented previously by two methods that use a grating in an extended cavity configuration: 1) use of a fiber Bragg grating (FBG) as the output coupler for an anti-reflection-coated semiconductor gain element<sup>1</sup>; 2) operation of an uncoated Fabry-Perot laser diode with optical feedback from a grating and RF-modulation of the drive current locked to the output power<sup>2</sup>. We have demonstrated CW single-frequency operation from a non-AR coated Fabry-Perot laser diode using only FBG optical feedback.

## 2. Theoretical basis

In the standard coupled-mode formalism<sup>3</sup>, the spectrum of a FBG is analysed using two counter-propagating modes, which are expressed (in the notation of Erdogan<sup>4</sup>) as:

$$\begin{aligned} R(z) &= A(z) \exp i(\delta z - \phi / 2) \\ S(z) &= B(z) \exp - i(\delta z - \phi / 2) \end{aligned} \quad (1)$$

where  $\phi/2$  is the  $z = 0$  phase of the incident beam. The solution for  $B(0)$  provides the reflectivity spectrum of the grating,  $\rho$ :

$$\rho = \frac{-\kappa \sinh(\sqrt{\kappa^2 - \hat{\sigma}^2} L)}{\hat{\sigma} \sinh(\sqrt{\kappa^2 - \hat{\sigma}^2} L) + i\sqrt{\kappa^2 - \hat{\sigma}^2} \cosh(\sqrt{\kappa^2 - \hat{\sigma}^2} L)} \quad (2)$$

Under a shift of the incident phase,  $\phi/2 \rightarrow \phi/2 + \Delta\phi/2$ , the phase of the two modes transforms as:

$$\begin{aligned} R(z) &\rightarrow \exp(-i\Delta\phi / 2) R(z) \\ S(z) &\rightarrow \exp(i\Delta\phi / 2) S(z) \end{aligned} \Rightarrow \rho \rightarrow \exp(i\Delta\phi / 2) \rho \quad (3)$$

In other words, the phase of the reflected beam is conjugate to that of the incident beam. This property can be reconciled conceptually by regarding the phenomenon as a one-dimensional four-wave mixing experiment in which the hologram was written permanently during an earlier exposure. At the short-wavelength band edge,  $\hat{\sigma} = +\kappa$ , the phase of  $\rho$  is zero ( $\kappa$  is real for single-mode fiber), so that reflected light at this wavelength will interfere constructively with its source, regardless of the location of the source.

When feedback is supplied to an uncoated Fabry-Perot laser diode from a FBG whose passband is narrower than the axial-mode spacing of the laser, the laser is selectively injection seeded by light near the Bragg peak of the FBG, stabilizing the laser oscillations within one axial mode. If the laser is temperature tuned so that the wavelength of the axial mode coincides precisely with the short-wavelength band edge of

the FBG, only laser oscillations at that wavelength will be constructively reinforced by the feedback, phase-locking the laser to single-frequency operation.

## 2. Experimental set-up

We coupled a nominally 935 nm Fabry-Perot laser diode (Sensors Unlimited) into an angle-cleaved, ultra narrow-band (18 pm), 16% reflectivity FBG (Kromafibre, Inc.) with a reflection peak at 935.562 nm using the configuration depicted in Fig. 1. The laser temperature was controlled by an analog TEC with 1 mK resolution (Wavelength Electronics HTC 3000). The emission at the laser facet was imaged 1:64 onto a beam profiler (BeamScan), and the spectrum characterized using an OSA (HP 7000A), a wavemeter (Burleigh WA-1500), and a scanning Fabry-Perot étalon (Burleigh). The optical-heterodyne measurement of the single-frequency linewidth used a Si-PIN detector (ThorLabs DET 210) with an RF spectrum analyzer (HP 8590A).

For best coupling into single-mode fiber, the astigmatic laser beam was collimated on the fast axis, placing the virtual beam waist of the slow axis 1.25  $\mu\text{m}$  behind the facet. To accommodate the resulting mode mismatch with the anastigmatic feedback signal, we used a variable aperture stop on the slow (lateral) axis of the collimated beam. This displaced the lateral focus of the feedback signal<sup>5</sup> to coincide with that of the laser for a slit width of 1.45 mm..

## 3. Results

We tuned the laser wavelength, subject to feedback from the FBG, by varying its temperature. The spectral purity of the output, as measured by side-mode suppression ratio, is seen in Fig. 2 to track the reflectance curve of the FBG, offset about -3 pm to the band edge of the grating, as predicted.

Detailed examination of the output at different wavelengths reveals three characteristic spectra. The first is observed for points that follow the reflectivity curve, whose spectra are stabilized within one axial mode of the laser cavity but are relatively broad. The second spectrum is seen at points such as the two outlying points at the top of Fig. 2. The spectrum at such a point is plotted in Fig. 3 and is seen to comprise several phase-stabilized submodes, spanning about 7 GHz--the approximate bandwidth of the FBG. The third spectrum displays true single-frequency operation, also plotted in Fig. 3. This occurs at the phase-stabilizing temperature when the optical alignment adjusted to precisely mode-match the injected signal to the laser mode, phase-locking a single submode. The submodes are believed to be caused by previously observed, fine-scale interferometric ripples in the spectrum of the FBG<sup>6</sup>.

We characterized the linewidth of the laser by mixing the laser output (935.562 nm) with the output from an ECDL<sup>7</sup> tuned to 935.564 nm and measuring the RF spectrum of the power beat note at the detector. The instantaneous (20 ms) linewidth was 225 MHz (not shown) and the time-averaged (2 s) linewidth was 470 MHz (Fig. 4).

A distinctive interferometric pattern arises in the lateral beam profile exclusively during single-frequency operation. The aperture stop used to accommodate the astigmatism acts as a hard aperture along the slow axis: 98% of the incident power passes through the aperture, but 55% of the feedback power is blocked

because of the smaller (0.12) numerical aperture of the fiber. The feedback profile drops only 4% from the center to the aperture edges, creating a nearly sinc-function diffraction pattern at the laser facet. The width of the sinc-function's central lobe for the optimal 1.45 mm aperture is 4  $\mu\text{m}$ ; this value matches the measured 4.2  $\mu\text{m}$  (lateral) beam waist of the laser. These values coincide because the lateral dimension of the laser waveguide mode is determined primarily by spatial variation in the gain profile, which also induces a uniform radius of curvature in the lateral plane<sup>8</sup>. Mode matching occurs when the curvature of the feedback beam coincides with that of the laser mode--when the beam waists match.

The beam curvature associated with the nonlinear gain profile corresponds to a virtual beam waist 1.25  $\mu\text{m}$  within the gain medium. The Fresnel number of the aperture<sup>9</sup>,  $w$ , formed by the diffracted feedback signal is constant along the waveguide mode and equal to the Fresnel number at the virtual beam waist,  $z_0$ :

$$N_f = \frac{(w/2)^2 n}{z_0 \lambda} = 12.5 \quad (4)$$

Mixing between the laser mode and feedback in the gain medium produces Fresnel ripples in the lateral beam profile, shown in Fig. 5, in good agreement with the calculated Fresnel number. At 5.8 mW power, only the central lobe of the sinc function lies above threshold in the gain medium, creating a "hard" aperture and large Fresnel ripples. With increasing power, the side lobes rise above gain threshold, softening the effective aperture and decreasing the observed modulation depth of the Fresnel ripples (not shown).

The P-I characteristic curves for the laser are presented in Fig. 6. Single-frequency operation is seen to lower the lasing threshold by 15.3% and increase the slope efficiency by 5.3%.

The same experiment was repeated with an SDL 7311 buried heterostructure laser and a 0.15 nm bandwidth FBG centered at 666 nm. In this instance, stable single-frequency operation (-50 dB side-mode suppression) was achieved without the use of a lateral aperture stop. We infer from this result that rigidly confining the gain region within the confines of the waveguide sufficiently reduces spatial variation of the gain profile to nearly eliminate astigmatism and the associated mode-mismatch phase ambiguity.

## References

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## Figure Captions

FIG. 1. Experimental setup including linewidth measurement (dashed lines).

FIG 2. Spectral purity of laser output versus wavelength with overlay of fiber Bragg-grating reflectance spectrum.

FIG 3. Scanning Fabry-Perot étalon spectrum of single-frequency operation (dotted line) and phase stabilized operation (solid line) with overlay of ramp-voltage trace. Resolution is 275 MHz.

FIG. 4. Time-averaged (2 s) RF spectrum of power beat note of laser with ECDL. Resolution bandwidth is 300 kHz.

FIG 5: Single-frequency (solid line) and frequency-stabilized (dotted line--laser temperature detuned by 12 mK) lateral beam profiles showing Fresnel ripples during phase-locked operation.

FIG. 6. Output power versus drive current for single-frequency (circles) and multi-frequency (dots) operation.

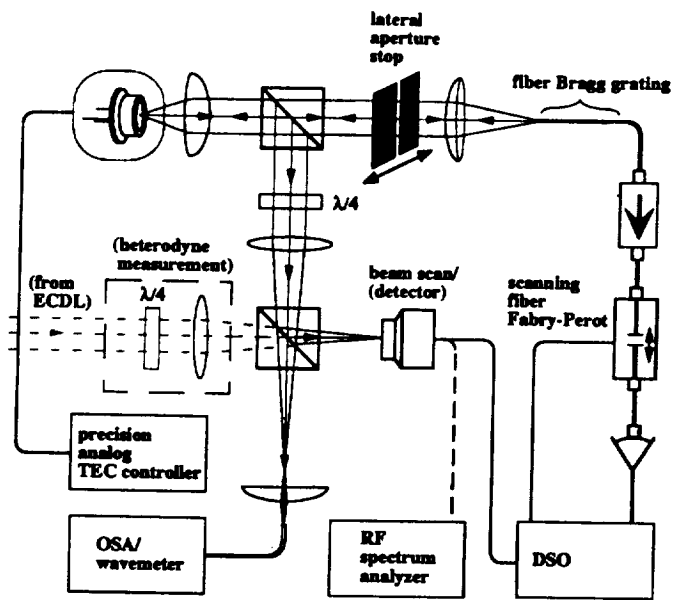


Figure 1  
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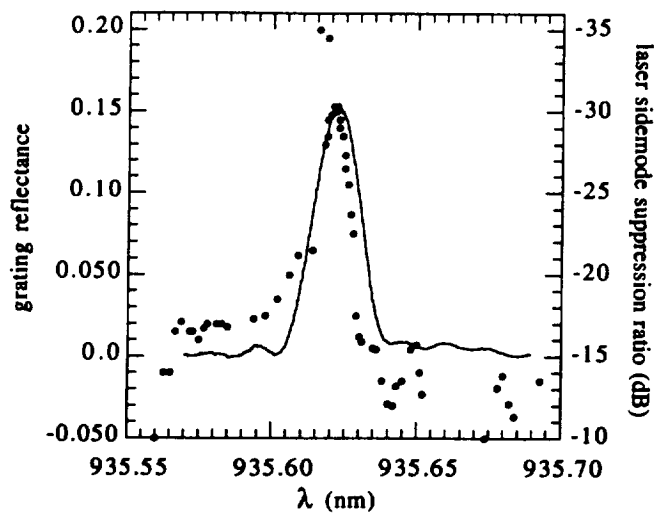


Figure 2  
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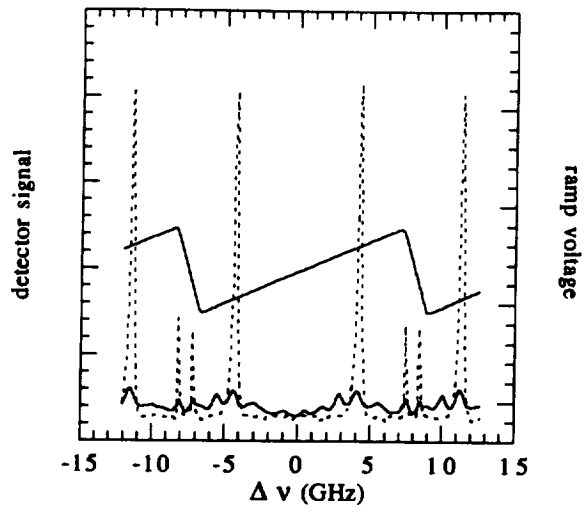


Figure 3  
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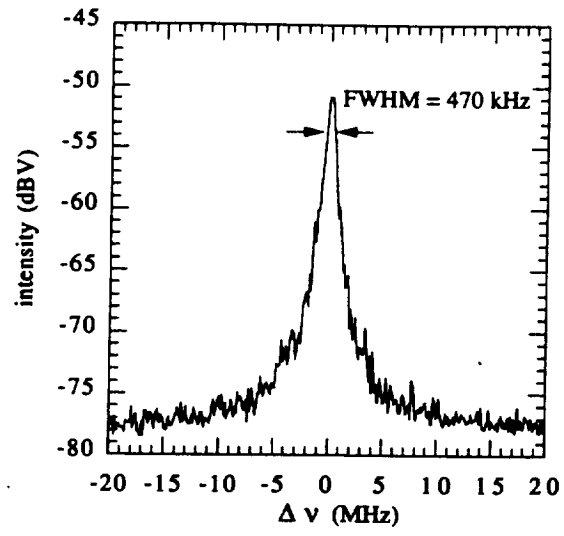


Figure 4  
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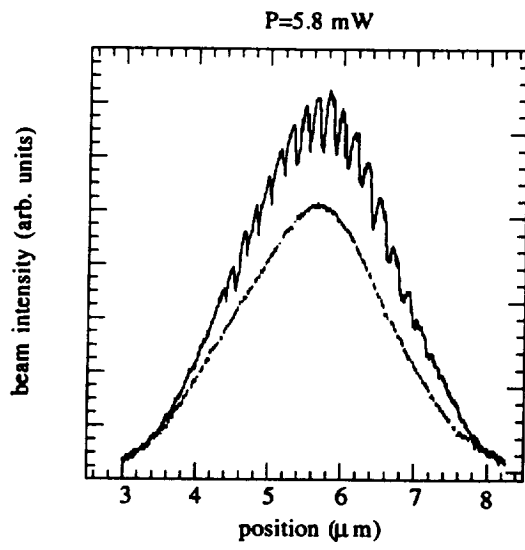


Figure 5  
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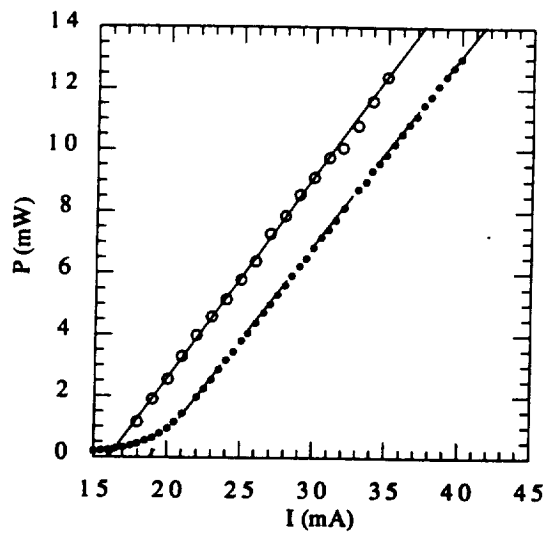


Figure 6  
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