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# Towards optical fiber synthesis of millimeter waves

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**Abstract**—Towards an optical synthesis of low phase noise continuous millimeter waves in a compact and an all-fiber system, we present the all-electrical locking of the optical frequency of a distributed feedback laser (DFB) diode at 1549 nm tunable over 2 nm, on a fibered Fabry-Perot (FP) cavity. We demonstrate a 6 MHz servo bandwidth and a frequency noise suppression down to  $3 \cdot 10^{-1}$  Hz/ $\sqrt{\text{Hz}}$  at 80 kHz carrier offset frequency in the error signal. Furthermore, we use a Brillouin fiber laser in order to refine the stabilized laser linewidth and we then demonstrate a frequency noise suppression down to 4 Hz/ $\sqrt{\text{Hz}}$  at 1 MHz offset frequency, limited by the phase noise floor of the measurement instrument.

**Keywords**—Feedback; Phase noise; millimeter wave generation; Cavity resonators

## I. INTRODUCTION

Tunable continuous millimeter electrical wave sources are the basis of a wide array of applications from the rovibrational spectroscopy of molecules [1] to radar applications [2]. The generation of such sources by a beat note of two optical carriers enables a wide tunability over hundreds of GHz frequencies [3,4].

For a compact, low cost, versatile and all-fiber system design, we choose two similar commercial DFB diode lasers to produce the beat note rather than solid state and extended cavity lasers, at the expense of a larger linewidth. Furthermore, laser diodes provide reliability and wavelength tuning without mode jump. We use the temperature of the laser chips in order to tune each laser wavelength and obtain the desired beat note frequency on a scale of hundreds of GHz. We also change the laser current to bring each laser optical carrier to resonance of a single Fabry-Perot cavity. We then have a beat note frequency equal to a multiple of the cavity free spectral range. The frequency noise of the beat note is then not sensitive at first order to the common mode cavity length fluctuations.

We report as a first step towards a millimeter wave source, the optical frequency stabilization of a tunable DFB laser on a fibered FP cavity in an all fiber system. We present in the second section of this paper the concept of the optical frequency stabilization by the using of a PDH (Pound Drever Hall) technique [5] with fast and slow servo loop paths. In the third section, we show experimental measurement results of the

frequency noise suppression by the servo loop and by the additional Brillouin fiber laser. We show also the phase amplitude coupling into the FP cavity and we discuss its effect on the relative intensity noise (RIN).

## II. EXPERIMENTAL SETUP

The DFB diode laser (EBLANA) has a 112 kHz linewidth and a 150 Hz/ $\sqrt{\text{Hz}}$  frequency noise floor extending over 100 MHz. Because of this wide frequency noise floor of the laser, we have created at first a LT spice model [6], in order to determine a unity gain frequency such that the root mean square values of both error and correction signals do not saturate. A high unity gain frequency will increase the frequency noise suppression band. The high unity gain frequency is limited to 6 MHz extra loop delay in this configuration; for that we have worked to decrease the open loop delay by shortening the servo loop path to a minimum, and we allowed for a larger frequency correction bandwidth by using two different actuators. Furthermore, the LTspice model allowed us to optimize the design of the correction electronics and to select for each function the fastest operational amplifiers.

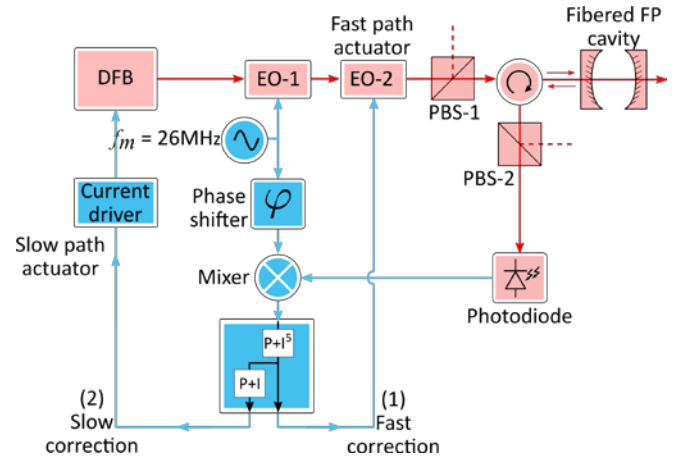


Fig. 1. Scheme of the all fiber system (DFB laser diode, cavity) with a two path electronic servo loop. EO: electro-optic modulator; PBS: polarizing beam splitter.

In the Fig. 1, we show the scheme of the DFB laser diode stabilization on the fibered FP cavity with a 1 MHz linewidth and a 1 GHz free spectral range. The DFB laser is operated at 1549 nm at 25°C, and generates a 4.3 mW optical power at 192

mA injection current by a low noise driver (VESCENT).

To generate the error signal, we used a PDH technique. The optical carrier is phase modulated at a 26 MHz modulation frequency  $f_m$ . The phase modulated wave was injected in the cavity through a 50/50 coupler used as a dual polarization fibered circulator. A frequency-filtered optical signal is transmitted through the cavity. The reflected optical signal is detected by a trans-impedance photodiode with a 110 MHz bandwidth. The output voltage is mixed with a phase shifted modulation signal at  $f_m$  in order to give the error signal. This error signal enters in an electronic control circuit with proportional and integrator function filters in order to provide a stable servo loop. This circuit was designed to maximize the unity gain frequency and minimize the error signal. The correction signal was divided over two different actuators, a fast (1) and slow (2) correction paths. First, an electro-optical phase modulator (EO-2) with a 150 MHz bandwidth and a  $3.2 \text{ V V}\pi$  was used to adjust the phase of the laser; the optical beam instantaneous frequency correction is proportional to the time derivative of the applied voltage. The fast loop had a 6 MHz bandwidth. This phase modulator was not able to correct the low frequency components of the instantaneous frequency fluctuations; for that we used a second actuator by introducing a bias on the driver current with a 127 MHz/mA coefficient; the optical frequency and the injection current are proportional by the Henry factor in a semiconductors [7]. The slow path also avoids the saturation of the fast correction signal by reducing its magnitude over a 350 kHz bandwidth.

We have also developed a Brillouin fiber laser cavity [8] at the output of the FP cavity in order to reduce the stabilized DFB laser linewidth. We use a 100 m highly nonlinear fiber as a medium gain. The output of the Brillouin fiber laser is detuned by 9.6 GHz frequency.

### III. EXPERIMENTAL RESULTS

In Fig. 2, we show the linear spectral density of the frequency noise of our DFB diode laser before and after locking, as well as downstream of the Brillouin fiber laser. The frequency noise of the free running laser (curve A) was measured in an autoheterodyne setup [9]. It comprises in the first arm an acousto-optic modulator at 80 MHz and in the other arm a  $L = 700 \text{ m}$  length standard fiber. The curve B represents the measure of the error signal calibrated by the transfer function of the measurement chain, it displays a frequency noise suppression down to  $3.10^{-1} \text{ Hz}/\sqrt{\text{Hz}}$  at 80 kHz carrier offset frequency. We calculate a 100 kHz root mean square excursion frequency value in the error signal. We also measure the frequency noise of the 9.6 GHz beat note between the stabilized laser in the cavity transmission used as a pump and the Brillouin laser output (curve C). We observe a degradation of the frequency noise in the cavity transmission below the 200 kHz offset frequency with respect to the error signal. We consider that this is due to an amplitude-phase coupling into the FP cavity originated from the optical power noise. Finally, in the curve D we show the auto-heterodyne measurement of the Brillouin output pumped by the stabilized laser. We have frequency noise suppression down to  $4.10^{-1} \text{ Hz}/\sqrt{\text{Hz}}$  at 100 kHz offset frequency: this corresponds to a phase noise at -108 dBc/Hz of the optical carrier. Above 100 kHz offset frequency the auto-heterodyne measurement is limited by the phase noise floor of the electrical spectrum analyzer (dashed line).

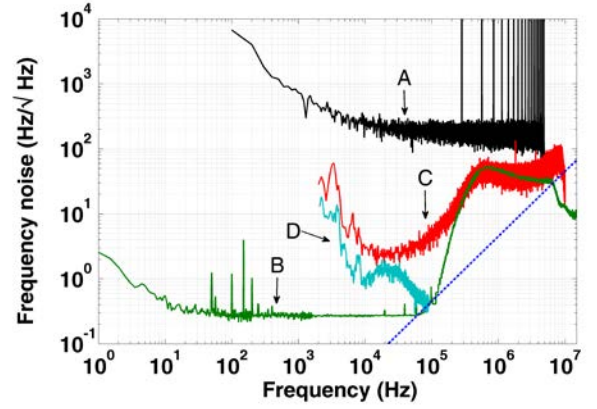


Fig. 2. Frequency noise linear spectral densities of the free running DFB laser (curves A) and locked represented by the error signal (curve B) and in the cavity transmission (curve C). Frequency noise of the Brillouin fiber laser pumped by the stabilized DFB laser (curve D). The frequency noise floor of the electrical spectrum analyzer is in dashed line.

Fig. 3 shows the linear spectral density of the relative intensity noise (RIN) in  $1/\sqrt{\text{Hz}}$ . In the locked mode (curve A), the relative intensity noise in the cavity transmission is degraded with respect to the free running laser (curve B). We consider that is a phase-amplitude (PM-AM) coupling into the FP cavity; we calculate it with the following procedure: we generate a time-domain envelope data whose frequency noise spectral density is the measured one; we then filter the instantaneous frequency by a low pass filter at a cut-off frequency  $f_c$  where  $f_c$  is the cavity half linewidth, to obtain  $v_f(t)$ ; then we apply a nonlinear transformation  $0.5 v_f^2(t)/f_c^2$ , followed by a low pass filter. We then estimate the linear spectral density of the amplitude fluctuations (curve C) in good agreement with the measured one.

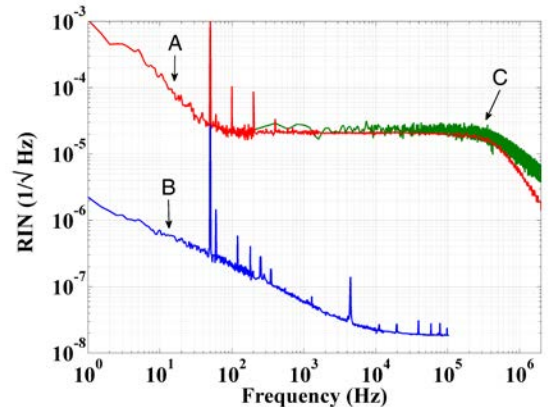


Fig. 3. Relative intensity noise linear spectral densities of the free running DFB laser (curve B), locked (curve A) and calculated from the PM-AM (Phase-Amplitude) coupling into the cavity (curve C).

### IV. CONCLUSION

We present in this paper a stabilization of the optical frequency of a DFB laser diode at 1549 nm tunable over 2 nm on a fibered Fabry-Perot cavity in an all fiber system. The PDH technique with a two-path servo loop has enabled us to achieve a unity gain frequency up to 6 MHz. A frequency noise suppression down to  $3.10^{-1} \text{ Hz}/\sqrt{\text{Hz}}$  at 100 Hz offset frequency in the error signal has also been demonstrated and we noticed a relative intensity noise degradation to  $2.10^{-5} 1/\sqrt{\text{Hz}}$  at 100 Hz in

the cavity transmission. We have also used a Brillouin fiber laser in order to refine the stabilized laser linewidth and obtain frequency noise suppression down to  $4 \cdot 10^{-1}$  Hz/ $\sqrt{\text{Hz}}$  at 100 kHz offset frequency.

We could improve the unity gain frequency by shorter or integrated fibered components. In a further step, the stability of the cavity would be improved by the stabilization of its free spectral range on a radio frequency synthesizer. Polarization beam splitters (PBS-1 and PBS-2) in the assembly (Fig. 1) will allow the future generation of a beat note between two DFB lasers.

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