Synthesis of a 30 Hz linewidth wave tunable over 500 GHz

Ayman Hallal, Steve Bouhier and François Bondu

Abstract—**We report on a compact source of 30 Hz linewidth, low phase noise electrical waves with a 500 GHz tunability. These waves are generated by photomixing two distributed feedback (DFB) laser diodes at 1550 nm which are frequency stabilized on a fibered cavity. We demonstrate a phase noise suppression down to -90 dBc/Hz at 100 kHz carrier offset frequency of the beat note at 2 GHz, 10 GHz, 18 GHz, 40 GHz and 92 GHz frequencies. The setup also displays a ~170 kHz frequency drift of the beat note at 10 GHz on the long term over a continuous 7.5 hour locking period.**

Index Terms—**Optical beat note, millimeter and submillimeter waves, phase noise, cavity resonators.**

I. Introduction

Tunable continuous micro-, millimeter and submillimeter low phase noise wave sources are required in many applications such as rovibrational spectroscopy of molecules [1], radar [2] and modern communication applications with reconfiguration abilities which use high frequency bands [3], [4] reaching some THz frequencies [5], [6]. There are various ways to produce continuous and stable millimeter or submillimeter waves [7]: by up-conversion of electrical waves, by direct generation or by down-conversion of optical waves. In the up-conversion of electrical waves, the phase noise power spectral density is degraded when transferred to the terahertz source and the tunability is limited by the waveguide bandwidth, about 30% of the upper frequency, so that several waveguides, multipliers, amplifiers, etc. are needed to cover the 1 GHz-1 THz band. A compact gas sensor based on rotational spectroscopy that covers the 210-270 GHz band has been demonstrated using an electrical source [8]. Sources of continuous waves that produce radiation directly in the terahertz band have a low tunability, following the example of quantum cascade lasers [9] that can achieve a carrier frequency excursion of a few percent [10]. The beat note of two optical carriers at 1.55 µm on a UTC photodiode [11], or at 800 nm on a LTGaAs antenna [12] allows the generation of waves up to a few THz [13], [14]. The frequency range in photomixing setups is mostly determined by the properties of the antenna emitting in free space. The accessible frequency range is then of the order of 90% of the maximum frequency. In a rotational spectroscopy setup for example, an increase of the accessible frequency range allows an increase of the set of accessible molecules, thus an increase of the information output: the photomixing technique seems promising. Another interest in frequency down conversion of optically generated waves is the ability to produce ultra-low phase noise microwave sources [15], [16]. When the millimeter or submillimeter radiation is generated by optical means, a stabilization loop of the optical carriers is generally required to compensate the optical carrier frequency noise and drift. There are several stabilization strategies: phase locking of the terahertz wave [17], frequency locking of the optical carriers on an optical reference [18], [19], phase locking of the beat note down-converted to lower frequencies [20], [21]. The phase locking of terahertz waves involves the use of complex mixers such as hot electron bolometers [17]. The stabilization of the optical carriers on a cavity has the advantage that the setup parameters are independent of the frequency of the generated millimeter or submillimeter wave.

In our previous work [22], we demonstrated a low cost and all fiber millimeter / submillimeter source with wide tunability properties. The photomixing of two commercial narrow linewidth lasers at 1.55 µm made a one terahertz range accessible. We stabilized the lasers with orthogonal polarizations on a commercial fibered Fabry-Perot (FP) cavity using an all electrical feedback loop, thus transferring the relative dimensional stability of the cavity to the beat note relative frequency. However, the error and correction signals saturated from time to time (order of 1 ms) inducing phase jumps on the beat note. Furthermore, the large optical phase noise generated optical amplitude fluctuations into the FP cavity.

In this paper, we present the advances on the performance of the source, especially on the phase noise and robustness properties. The beat note frequency is a multiple of the 1 GHz cavity free spectral range. We then present the phase noise performance of waves with a carrier frequency limited by our 108 GHz photodiode bandwidth. In the second section, we present the basis of the optical frequency stabilization of the DFB lasers on a fibered FP cavity. We also show experimental results of the frequency noise suppression of the stabilized DFB laser in the cavity transmitted light. In the third section, we present the beat note experimental setup and in the fourth section the phase noise measurements at 2, 10, 18, 40 and 92 GHz beat notes frequencies. We also characterize the beat note frequency stability on the long term and the electrical power spectrum of the beat note.

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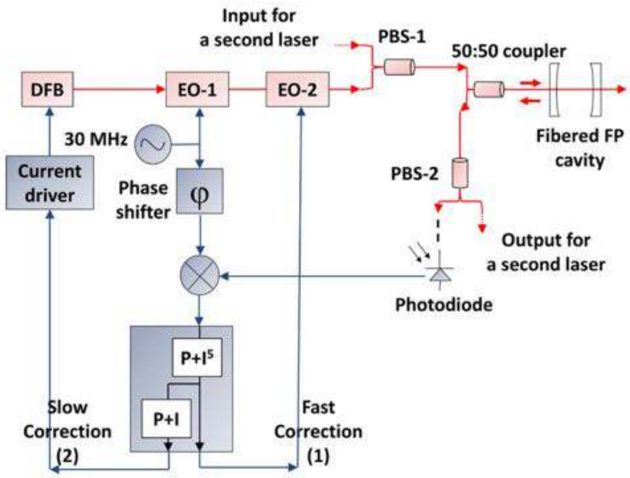

Fig. 1. Scheme of the all fiber system (DFB laser diode, cavity) with a two path electronic servo loop. EO: Electro-Optic; PBS: Polarizing Beam Splitter; FP: Fabry-Perot; P: Proportional; I: Integrator; I^5: chain of five integrators in series.

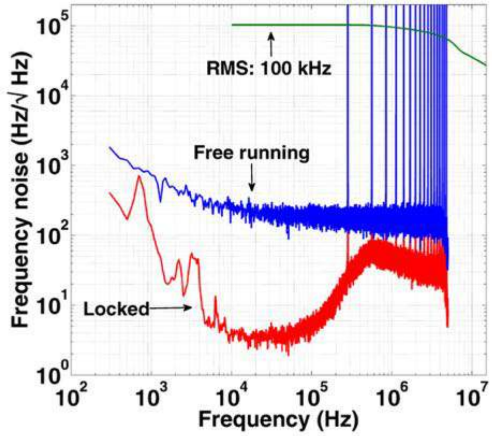

Fig. 2. Frequency noise linear spectral densities of the free running and locked DFB laser with the calculation of the root mean square RMS frequency excursion.

II. Frequency stabilization of a DFB laser

We implement some improvements with respect to our previous work which suppress the error signal saturation and reduce the frequency noise in the cavity transmitted light beam. Firstly, we use an EBLANA DFB laser diode (160 Hz/√Hz frequency noise floor extending over 100 MHz) with a linewidth reduced by a factor of 6 compared to the previous work one at the expense of a measured tunability reduced from 9 nm to 4 nm. Secondly, we use a FP cavity with a 1 GHz free spectral range and a 1 MHz linewidth, this latter being smaller by a factor of 15 than the one used in the proof of concept. With a smaller linewidth cavity, there is stronger filtering at offset frequencies larger than the cavity pole. However, the error signal could also saturate at lower levels of frequency excursion. We experimentally test that the first effect arises before the second one, so unlike our first intuition, it is actually easier to stabilize a laser with frequency noise with contributions at high offset frequencies on a small linewidth cavity.

In the experimental frequency stabilization of a single DFB laser (Fig. 1) we operate it at a wavelength of 1549 nm with a 192 mA injection current at 25°C. The wavelength is tuned over the cavity resonances by changing the laser chip temperature. We measure a wavelength tunability over 4 nm for a DFB laser chip temperature from 0 to 50°C. We use the laser current to bring one wavelength on a resonance of the cavity. The error signal is generated with the Pound-Drever-Hall technique [23]. The optical wave of the laser is phase modulated by an electro-optic phase modulator (EO-1) at a 30 MHz modulation frequency to create two side bands around the laser carrier, before being injected in the fibered cavity through a 50:50 coupler used as a dual polarization circulator. The reflected ligh beam of the cavity is detected by a transimpedance photodiode with a 100 MHz bandwidth and then is demodulated by a phase shifted signal at 30 MHz, to finally obtain an electrical error signal whose amplitude is proportional to the difference of the instantaneous frequency of the laser and of a resonance frequency of the cavity. We use a fast (1) and a slow (2) servo loops for the frequency correction. The former allows a low excursion frequency noise correction with a 7 MHz servo bandwidth and the latter corrects the instantaneous frequency fluctuations with a 350 kHz servo bandwidth. The fast servo loop adjusts the phase of the laser with an electro-optic phase modulator as an actuator (EO-2); the optical beam instantaneous frequency is proportional to the time derivative of that phase. The fast servo loop has a 3.5 m length, implying a 18 ns open loop delay which finally limits our servo bandwidth to 7 MHz. The electro-optic phase modulator is not able to correct the frequency noise at low carrier offset frequencies. Thus, the slow servo loop modulates the injection current of the laser with a 127 MHz/mA low noise current driver (VESCENT): the optical frequency and the injection current of the laser diode are related by the Henry factor [24]. Furthermore, the slow correction signal helps to reduce the magnitude of the fast one, thus avoiding saturations.

We have designed an electonic control circuit with multiple proportional and integrator function filters maintaining stable servo loops and minimizing the error signal. An LTspice design and simulation of this circuit allows us to select the fastest operational amplifiers in order to maximise the phase margin. The LTspice model of the servo loop is also created including a realistic frequency noise value of the free running laser, the electronic control circuit and the transfer functions of the error signal chain measurement and of the actuators. We reduce the slow and fast servo loop gain peakings such that the root mean square value of the linear spectral densities of the error signal is four times smaller than its peak value and such that the correction signal root mean square value is 25 times smaller than the supply voltage of the electronic control circuit.

Fig. 2 shows the linear spectral densities of the frequency noises of the free running DBF laser and of the frequency stabilized laser transmitted by the cavity. Frequency noises are measured with an auto-heterodyne setup [25] with an

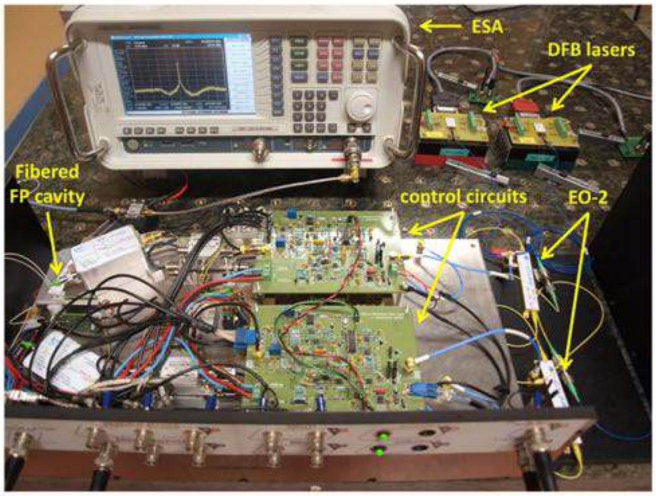

Fig. 3. Photograph of the frequency stabilization of the two DFB lasers with an electrical spectrum analyzer (ESA) measuring the electrical power spectrum of a beat note at 10 GHz. EO: Electro-Optic; FP: Fabry-Perot.

asymmetric interferometer. The frequency noise is suppressed down to 4 Hz/√Hz at 10 kHz carrier offset frequency. However, below this offset frequency, we observe a strong rise of the frequency noise which we attribute to the cavity length fluctuations. We also calculate a 100 kHz root mean square frequency excursion from 10 kHz to 15 MHz integration frequency range, much smaller than the cavity linewidth: the error signal does not saturate.

III. Beat Note Experimental Setup

After the stabilization of the DFB laser, we realize a servo loop with a second similar DFB laser. We stabilize the optical frequency of the second laser in the same fibered FP cavity. The two optical carriers are combined by a polarization beam splitter (see Fig. 1, PBS-1) making two orthogonal polarizations, thus avoiding power fluctuations in the cavity at the beat note frequency. A second PBS-2 also separates the reflected light wave from the cavity towards the error signal detection of each servo loop. Our DFB lasers have optical frequency tuning ranges that overlap by about 88% and then the stabilized lasers generate a beat note frequency tunable from 1 GHz to 500 GHz, with a step of 1 GHz equal to the cavity free spectral range. Another choice of laser chip overlap range may allow a tunability up to 1 THz. Fig. 3 shows a photograph of the setup of the frequency stabilization of the two lasers together with an electrical spectrum analyzer (ESA) measuring the electrical power spectrum of a beat note at 10 GHz. The box includes simultaneously the electronic control circuits, photodiodes, mixers and other electrical components on the top layer and the fibred FP cavity, electro-optic phase modulators and other optical components on the bottom layer. This arrangement minimizes the connection lengths between the electrical and the optical components.

Fig. 4 shows the scheme of the beat note generation and the phase noise measurement setups of the beat note at 2 GHz, 10 GHz, 18 GHz (a), at 40 GHz (b) and at 96 GHz (c). At all frequencies, we use a polarization controller followed by a 45°

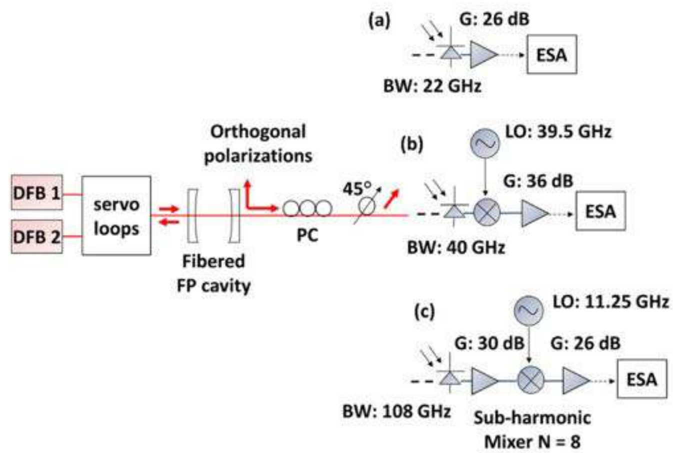

Fig. 4. Scheme of the beat note generation by two frequency stabilized DFB laser diode on a fibered FP cavity and of the phase noise measurement setups of the frequency beat note at 2 GHz, 10 GHz and 18 GHz (a), at 40 GHz (b) and at 92 GHz (c). ESA: Electrical Spectrum Analyzer; FP: Fabry-Perot; PC: Polarization Controller; BW: Bandwidth; G: Gain; LO: Local Oscillator; N: sub-harmonic Number.

polarizer to bring the two orthogonal polarization states to a common one, thus maximizing the optical power of the beat note signals. An average optical power of -17 dBm is measured at the output of the polarizer. At 2, 10 and 18 GHz beat note frequencies, a DISCOVERY LAB BUDDY photodiode with a 22 GHz bandwidth and a 0.7 A/W coefficient detects the optical beat note signal. The beat note signal is amplified with a 26 dB gain to be directly measured by a 32 GHz bandwidth electrical spectrum analyzer with a phase noise module. At 40 GHz beat note frequency, we use a NEW FOCUS photodiode with a 40 GHz bandwidth and a 0.45 A/W coefficient. A mixer with a 9 dB loss demodulates the beat note signal with a 39.5 GHz local oscillator. At the mixer output, a 475 MHz intermediate frequency signal is obtained and amplified with a 36 dB gain before it is detected by the ESA. Finally, at 92 GHz beat note frequency, a FINISAR photodiode with a 108 GHz bandwidth and a 0.59 A/W coefficient is followed by a 30 dB electrical amplifier. An N = 8 sub-harmonic mixer with a 36 dB loss demodulate the beat note signal with an 11.25 GHz local oscillator. At the output, a 1 GHz intermediate frequency signal is obtained and amplified with a 26 dB gain to be finally detected by the ESA.

IV. Experimental Results

Fig. 5 shows the measurements of the phase noise at 2 GHz, 10 GHz, 18 GHz, 40 GHz, and 96 GHz beat note frequencies from 1 kHz to 15 MHz carrier offset frequency. We observe a good similarity between phase noise measurements, with a -60 dBc/Hz phase noise at 1 kHz offset frequency and a phase noise of -90 dBc/Hz at 100 kHz offset frequency. At high carrier offset frequencies, the phase noise measurements are limited by the electrical thermal noise. We check that the minimum phase noise in dBc/Hz is as expected

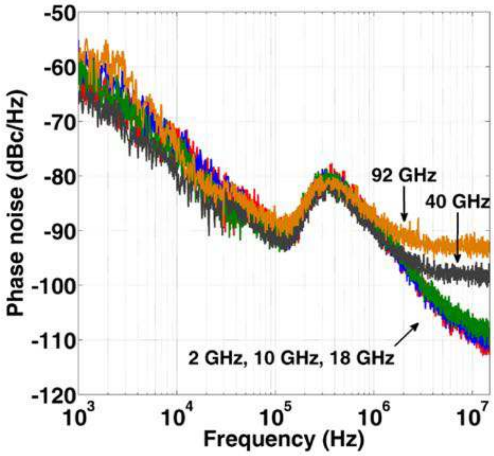

Fig. 5. Phase noise measurements of the beat note at 2 GHz, 10 GHz, 18 GHz, 40 GHz and 92 GHz frequencies.

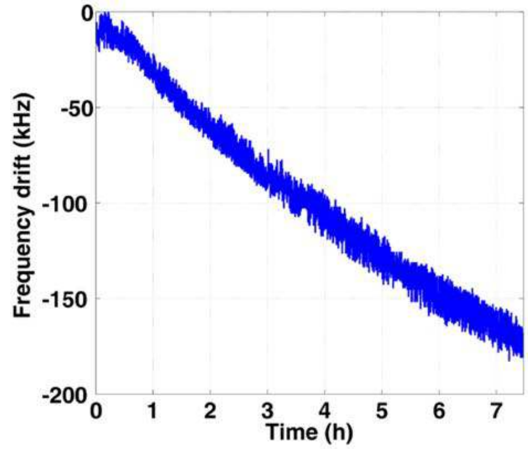

Fig. 7. Drift of the 10 GHz beat note frequency on the long term over a continuous 7.5 hour locking period.

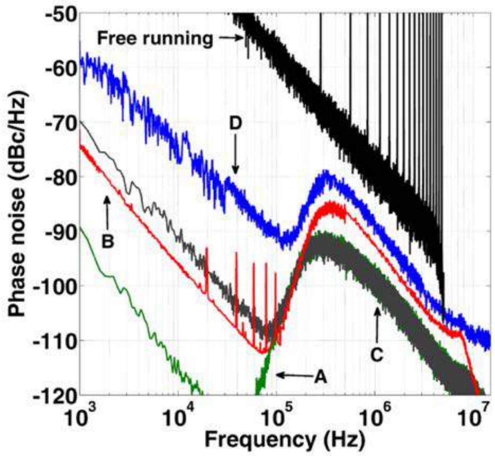

Fig. 6. Comparison between the simulated error signal (curve A), the measured one (curve B), the simulated error signal with the calculation of the induced non-linear effect on the error signal (curve C), the phase noise measurement of the beat note at 10 GHz (curve D) and the free running DFB laser phase noise.

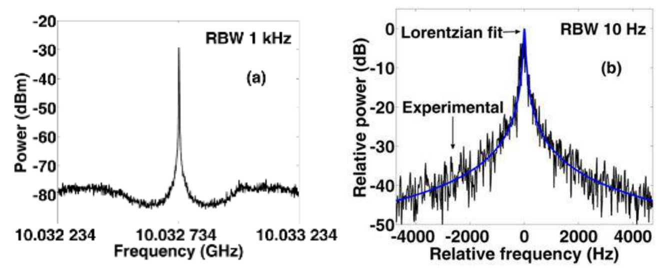

Fig. 8. Electrical power spectrum of the beat note at 10 GHz. (a) Measure with a span of 1 MHz and a resolution bandwidth RBW of 1 kHz and (b) measure with a span of 10 kHz and a RBW of 10 Hz, with a 30 Hz linewidth calculated from the Lorentzian fit function.

$$S_{\phi \min} = -174 + NF_{dB} + 10\log_{10}\left(\frac{\frac{1}{2}\frac{G_{AC}^2}{R_c}P_{opt,AC}^2}{1.10^{-3}}\right) \quad (1)$$

where NF_{dB} is the noise factor of the amplifier or the measurement chain connected to the photodiode, G_{AC} is the AC optical power to AC voltage conversion factor of the photodiode in V/W, $P_{opt,AC}$ is the peak optical power of the beat note and R_c is the load resistor. At 40 GHz beat note measurement, the phase noise floor increases to a -98 dBc/Hz due to the mixer loss which degrades the signal-to-noise ratio. At 92 GHz beat note measurement, the losses of the sub-harmonic mixer and of the connections are about 40 dB. A 30 dB electrical amplifier before this loss chain is useful to limit the signal-to-noise ratio degradation, to finally obtain a -92 dBc/Hz phase noise floor. An optical amplifier at the cavity output could improve the signal-to-noise ratio where limited by electrical thermal noise.

Fig. 6 shows firstly the simulated error signal (curve A). In our servo loop model, the curve A is the sum of two noise contributions: for offset frequencies above 40 kHz, the free running laser noise attenuated by the loop gain and filtered by the cavity pole, for offset frequencies below 40 kHz the input referred electronic noise of the control electronics. The curve B shows the measured error signal, different from the curve A. Actually, the laser frequency sweeps the Airy peak of the cavity resonance since the root mean square frequency is not infinitely small compared to the cavity linewidth. We calculate the induced non-linear effect on the error signal [22] to obtain the curve C, in better agreement with the measured one. The discrepancy by a few dB between B and C curves might be due to inaccurate modeling of the feedback loop. Finally, we compare the phase noise of the beat note at 10 GHz (curve D) with the measured error signal on a single DFB laser. The 3 dB difference between the two curves for frequencies greater than 200 kHz is explained by the statistical independence of the two free running frequency noises of the lasers. For offset frequencies below 200 kHz we observe a deterioration of the beat note phase noise with respect to the measured error signal: it is induced by a yet un-modeled additional noise on the error signal. The measurement of the free running DFB laser is converted in a phase noise and it is also showed in the Fig. 6.

We then measure the frequency stability of the 10 GHz beat note frequency on the long term (Fig. 7). The frequency drift is ~170 kHz over a continuous 7.5 hour locking period, implying a ~6.3 Hz/s average beat note frequency drift. A thermal stabilization of the cavity could improve the drift of the beat note on the long term. The stabilities of the optical carrier and of the beat note relative frequencies are equal to 8.10^{-6} 1/°C according to the cavity specification. So a 100 GHz beat note a frequency drift lower than 100 kHz requires at temperature control at the 0.12°C level

Finally, we show the electrical power spectrum of the beat note at 10 GHz (Fig. 8). The measurement of the beat note (a) is taken with a span of 1 MHz and a resolution bandwidth RBW of 1 kHz. We see the power suppressions around the carrier due to the servo bandwidth loops of the lasers. In the Fig. 8 (b), the spectrum fits with a 30 Hz linewidth Lorentzian function. This measurement is taken with a span of 10 kHz and a resolution bandwidth RBW of 10 Hz over a 0.68 s sweep time, thus with a negligible contribution from the laser frequency drift. We estimate the same linewidth with a 92 GHz carrier. A Brillouin fiber laser could also refine the beat note linewidth [26], [27].

V. Conclusion

We show a compact source of low phase noise waves. Two frequency stabilized DFB lasers with a wavelength difference tunable over 4 nm on a fibered FP cavity, generate a widely tunable beat note from 1 GHz to 500 GHz. We demonstrate almost identical phase noise measurements of the beat notes at 2 GHz, 10 GHz, 18 GHz, 40 GHz and 96 GHz and a phase noise suppression down to -90 dBc/Hz at 100 kHz carrier offset frequency. A 30 Hz linewidth and a ~170 kHz frequency drift over a continuous 7.5 hour locking period of the beat note at 10 GHz is also been demonstrated.

The synthetized phase noise could be improved. According to our simulations, a 30 cm length integrated servo loop system could increase the servo bandwidth to 22 MHz. This would lead to a 30 kHz root mean square frequency excursion in the cavity transmitted light beam and a further 18 dB phase noise suppression at 1 MHz offset frequency on the error signal.

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