Highly Stable Microwave Carrier Generation Using a Dual-Frequency Distributed Feedback Laser

M.R.H. Khan[#1], E.H. Bernhardi[*2], D.A.I. Marpaung[#3], M. Burla[#4],
R.M. de Ridder[*5], K. Wörhoff[*6], M. Pollnau[*7], and C.G.H. Roeloffzen[#8]

[#]Telecommunication Engineering group, Faculty of EEMCS, University of Twente,
[*]Integrated Optical MicroSystems group, MESA+ Institute for Nanotechnology, University of Twente,
P.O. Box 217, 7500 AE Enschede, The Netherlands
e-mail: m.r.h.khan@ewi.utwente.nl

Abstract—**Photonic generation of microwave carriers by using a dual-frequency distributed feedback waveguide laser in ytterbium-doped aluminum oxide is demonstrated. A high-performance optical frequency locked loop is implemented to stabilize the microwave carrier. This approach results in a microwave frequency at ~14 GHz with a phase noise of -75 dBc/Hz at 1 MHz offset from the center frequency. The frequency stability of the photonic microwave carrier has an Allan deviation of better than 1×10^{-10} for an averaging time of 1000 s with a loop settling time of 15 µs.**

***Index Terms*—dual-frequency laser, microwave generation, frequency stability, optical frequency locked loop (OFLL).**

I. Introduction

Photonic generation and distribution of high spectral purity microwave or millimeter-wave carriers is interesting for applications like clock distribution, radar and antenna remoting because of stringent phase noise requirement [1-3]. Mowever, the optically generated microwave carriers should have excellent long-term frequency stability in order to meet the requirements prescribed by applications such as the receivers of millimeter interferometers like ALMA (Atacama large millimeter/sub-millimeter array) [2] or K_u-band (10.7 - 12.75 GHz) PAA system [3]. One method to optically generate a microwave carrier is to use optical heterodyning of two laser frequencies either between independent lasers or between two laser modes sharing a common gain and cavity [5]. In the first approach, all phase noise and drift from each laser is directly transferred onto the microwave carrier [6]. This approach also suffers from large frequency drift of the microwave carrier [7]. In the latter approach, referred to as a dual-frequency laser (DFL), the relative fluctuations between the two frequencies are low and can be used to generate a low-phase-noise microwave carrier due to the common-mode noise rejection effect [5, 8].

Recently, we have reported a dual-frequency distributed feedback (DFB) channel waveguide laser in ytterbium-doped aluminum oxide (Al_2O_3:Yb^{3+}) fabricated on a silicon substrate, which shows great potential for the monolithic integration of optically generated microwave sources [9]. The free-running DFL was used to generate a microwave beat signal at a frequency of ~15 GHz with a linewidth of 9 kHz. The long-term frequency stability over a period of 45 minutes was less than 2.5 MHz, while the power of the microwave carrier was stable within 0.35 dB during the same period. Although the long-term frequency stability of the free-running laser is much better than that of semiconductor lasers, it still does not meet the stringent frequency stability requirement prescribed by many applications.

The long-term free-running frequency stability of an optically generated microwave carrier can be improved when the DFL is inserted in an optical frequency locked loop (OFLL). In the OFLL the microwave beat signal is frequency-locked with a reference signal. The required speed of the loop for an OFLL is several orders of magnitude lower compared to an optical phase locked loop. Moreover, an OFLL provides a much wider capture range and orders-of-magnitude faster recovery when the microwave carrier unlocks [10]. By implementing an OFLL besides improving the frequency stability, a reduction in the phase noise can also be achieved. The frequency noise spectrum of a microwave carrier can be divided into two regions of interest. Noise at high offset frequencies from the center frequency (typically >100 kHz) is difficult to compensate by a feedback system. However, noise at lower offset frequencies from the center frequency, due to environmental and thermal drifts [11], can be compensated by locking the laser to a low-noise RF oscillator [12].

In this work we implement the locking of a dual-frequency Al_2O_3:Yb^{3+} DFB channel waveguide laser using an OFLL in order to improve the free-running frequency and power stability of the optically generated microwave, while also reducing the phase noise. The remainder of the paper is organized as follows. Section 2 and Section 3 describe the DFL and OFLL scheme, respectively. In Section 4, a frequency stability analysis is presented. Section 5 presents the loop response and phase noise of the microwave carrier. In the last section conclusions are drawn.

II. Dual-Frequency Laser Characteristic

Operation of the optically pumped DFL is based on two localized phase shifts in a straight-channel-waveguide DFB cavity. Fabrication of the waveguide and Bragg gratings is described elsewhere [9]. When two quarter-wavelength phase

This work is in the framework of the MEMPHIS project. The authors gratefully acknowledge the support of the Smart Mix Programme of the Netherlands Ministry of Economic Affairs and the Netherlands Ministry of Education, Culture and Science.

shifts are induced in a uniform waveguide Bragg grating, two resonances appear in the transmission stop-band of the device. These two resonances share a common cavity, which consists of both phase shifts, and the frequency spacing between the two resonances (lasing modes) depends on the spatial separation and values of the respective phase shifts in the cavity. The frequency spacing between the two laser modes is what ultimately determines the beat frequency at the output of the PD. In order to realize the two required quarter-wavelength phase shifts, two sections with 2-mm-long adiabatic sinusoidal widening of the waveguide width are fabricated [13]. The two quarter-wavelength phase shifts are centered at 4.5 mm and 6.5 mm respectively (as measured from the pumped end facet of the 1-cm-long cavity). The laser emission spectrum is centered at a wavelength of ~1020 nm and a measurement with the 40-GHz-bandwidth PD (New Focus 1011) confirmed the dual-frequency operation with a beat signal at 14.2 GHz.

III. Optical Frequency Locked Loop (OFLL) Scheme

In order to stabilize the generated microwave carrier, an OFLL is implemented, the block diagram is presented in Fig. 1. In such an OFLL the beat frequency, f_{beat}, from the PD is mixed with a stable RF reference signal, f_{ref}, provided by a signal generator (Agilent PSG E8267D). An error frequency, $f_e = f_{beat} - f_{ref}$, is produced at the output of the RF mixer (MiniCircuit ZX05-153LH-S). This signal, $V_e\cos(2\pi f_e t)$, is then passes through a variable RF discriminator, where V_e is the amplitude of the error signal. In the RF discriminator the signal is split into two parts which were recombined on a mixer, after one part have been delayed by a variable delay time, τ_1. The resultant output at the variable RF discriminator is

$$V_0 = \frac{V_e^{\,2}}{8}\left[\cos 2\pi f_e \tau_1 + \cos 2\pi f_e (2t - \tau_1)\right] \qquad (1)$$

Next the high-frequency term (2^{nd} term in the bracket) is eliminated with a low-pass filter (LPF). As a result, the mixer output produces a series of nulls when $f_e\tau_1 = (2n+1)/4$, where $n = 0, \pm1, \pm2...$ To achieve better loop control and stability the error signal is then fed to a proportional-integral-derivative (PID) controller for the purpose of tuning the loop gain and eliminating the static error. The error signal is sent to the pump laser in order to control its current and, consequently, the optical pump power. A change in the pump power changes the thermally induced chirp in the Bragg grating, which, in turn, changes the frequency separation between the two laser modes. The commercial pump laser current controller (Thorlabs PRO8000) of the DFL has an external tuning port having a voltage-to-current conversion factor of 200 mA/V. For the pump powers at which the DFL operates, the optically generated microwave carrier increases linearly with pump current at a rate of 180 kHz/mA.

We use a time delay of τ_1 = 3.3 ns, equivalent to 0.99 m of delay line, so that the OFLL allowes stable locking to several values of the beat frequency, which are spaced by $1/\tau_1$ = 300 MHz, corresponding to the zero crossings of the error signal. The locking point could be tuned by simply varying the RF reference signal. The locking range is given by $1/2\tau_1$ (= 150 MHz), which is much larger than the frequency

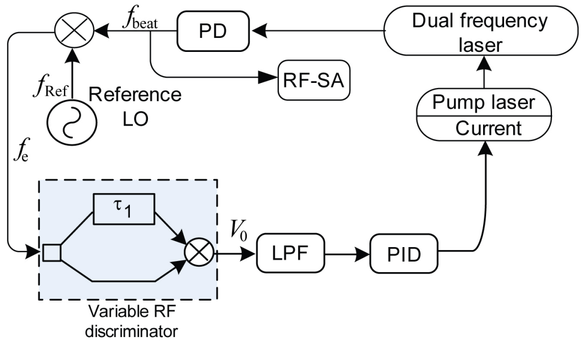

Fig. 1. Schematic of the frequency locked loop (FLL).
PD: photodetector, LO: local oscillator, LPF: low pass filter,
PID: proportional-integral-derivative, RF-SA: RF spectrum analyzer.

jitter (~2.5 MHz) of the free-running system, thus preventing the feedback loop from hopping between different locking points.

IV. Frequency Stability

A free-running microwave frequency, f_{beat}, deviates from the required frequency, f_{ideal}, with variable direction and speed. To evaluate this frequency stability, the Allan deviation, σ_y, has proven itself a valuable tool to quantify the stability of an optically generated microwave carrier [14]. The Allan deviation of the relative frequency error $y(t) = 1-(\Delta f_{LO}/f_{ideal})$ is defined by

$$\sigma_y(\tau) = \left[\frac{1}{2(M-1)}\sum_{i=1}^{M-1}\left(y_{i+1} - y_i\right)^2\right]^{1/2} \qquad (2)$$

where y_i is the i^{th} of M fractional frequency values averaged over the measurement (sampling) interval, τ. The measured long-term frequency stability of the free-running microwave carrier expressed in terms of the Allan deviation is shown in Fig. 2, where it increases from 3.5×10^{-10} at τ = 1 s to 5×10^{-9} at τ = 1000 s. However, the long-term frequency stability of the DFL could be improved to a value of $\sim1\times10^{-10}$ for τ ranging from 10 s to 1000 s by implementing the OFLL. The inset in Fig. 2 shows the measured frequency of the generated microwave carrier for both free-running and locked condition

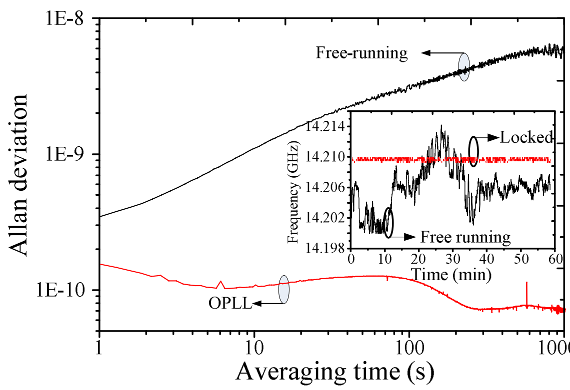

Fig. 2. Allan deviation of the DFL under free- running and locked condition. The inset shows the measured frequency stability of the microwave signal during a period of 1 hour.

during a period of 1 hour. During this same period the power stability of the microwave carrier is also improves from

0.35 dB to 0.11 dB by making use of the OFLL. These results emphasize the effectiveness of using the OFLL for improving the long-term stability of the free-running microwave carrier by enabling a 3-fold improvement in the power stability, as well as a 50-fold improvement in the frequency stability at 1000 s averaging time.

V. Loop Response and Phase Noise

From Leeson's well-known phase-noise model for oscillators [11], the random walk of the frequency noise is usually very close (<100 kHz offset) to the carrier. This is related to the oscillator's physical environment (mechanical shock, vibration, temperature, or other environmental effects) [11]. An OFLL can be used to reduce this low-frequency noise. This implies that the speed of the feedback loop should be on the order of MHz, which suggests that the response of the OFLL must be on the order of microseconds. The LPF is crucial in the design of the OFLL, as it can affect the loop response time, provided that the bandwidth of the LPF is large enough so that it allows the error signal to pass through. However, a large bandwidth will also allow more noise in the feedback system. With this trade-off in mind, we chose to use a LPF having a 3-dB bandwidth of 10 MHz. The time constant of the LPF determines the speed of the loop, which can be adjusted. Taking into account that the LPF used in the OFLL is a first-order LPF, the closed-loop transfer function, $H(s)$, of the OFLL is given by [15]

$$H(s) = \frac{\omega_n^{\,2}}{s^2 + 2\varsigma\omega_n s + \omega_n^{\,2}} \tag{3}$$

where s = $j2\pi f$, and ω_n and ζ represent the natural angular frequency and the damping factor of the loop, respectively, and are expressed by the following equations [15],

$$\omega_n = \sqrt{\frac{K_{SL} K_d K_a}{\tau_2 \tau_0}} \tag{4}$$

$$\varsigma = \frac{1}{2\omega_n \tau_2} \tag{5}$$

where K_d is the frequency-to-voltage conversion factor for the frequency discriminator and has a maximum value at the closest null to the reference frequency. Its value is found to be 300 mV/GHz. K_{SL} is the conversion factor of the applied voltage in the pump laser current controller and emission frequency of the DFL and is 36 kHz/mV. The time constant of the integrator in the pump laser controller, τ_0, and the LPF, τ_2, are 6 μs and 15.5 μs, respectively. The total gain of the RF amplifiers, K_a, used in the feedback loop is referred to as loop gain.

From Eqs. (4) and (5) we calculate the natural frequency ω_n = 40 kHz and damping factor ζ = 0.8 for a loop gain, K_a, of 11.8 dB. With K_a = 17.8 dB the natural frequency and the damping factor become ω_n = 80 kHz and ζ = 0.4, respectively. With the help of Eq. (3) we calculate the step response of the loop using the above values of natural frequencies and damping factors. The step response will provide an insight to the loop response time, also referred to as the settling time,

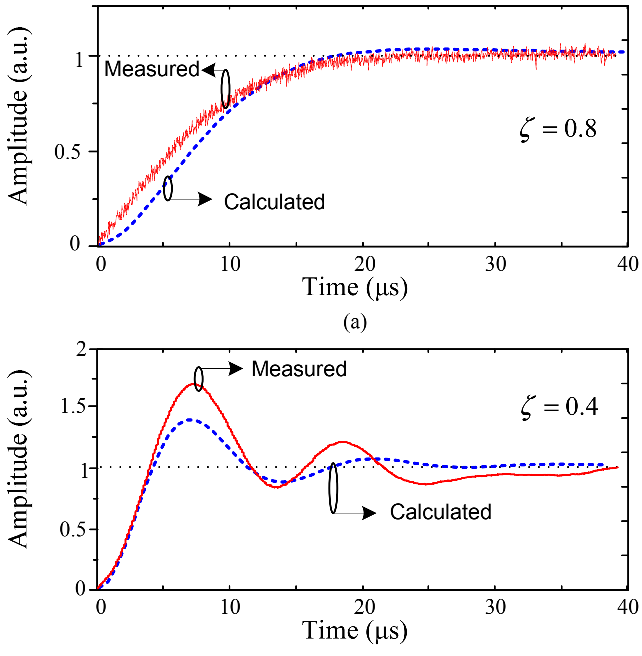

Fig. 3. Loop response time (settling time) comparison on calculated and measured values for various damping factors, ζ, using step response. (a) ζ=0.4 (b) ζ=0.8.

which represents the time taken for a feedback system to reach 90% of its final value. As shown in Fig. 3(a), the settling time is calculated and measured to be 15 μs for ζ = 0.8. For ζ = 0.4, the calculated and measured values of the loop response is found to be 24 μs and 28 μs, respectively, as shown in Fig. 3(b). These experimental values are in good agreement with the calculated values. From this result it is clear that the loop response time depends on the damping factor, ζ, and its proper choice depends on the values of loop gain and LPF.

As demonstrated in Fig. 3, the measured response of the OFLL is 15 μs for a loop gain of 11.8 dB. This provides a loop speed of 70 kHz. It ultimately means that the OFLL could improve the laser phase noise below an offset frequency of

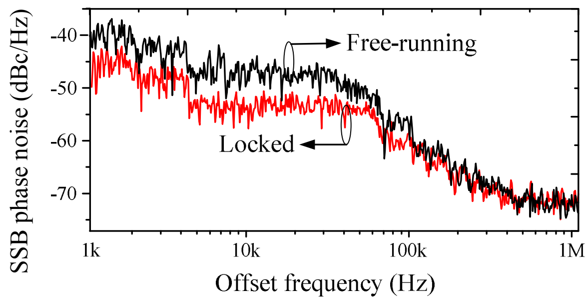

Fig. 4. Phase noise of the generated microwave.

70 kHz from the carrier. This is verified by phase noise measurements. The phase noise of the generated microwave carrier is measured for both free-running and locked conditions and is shown in Fig. 4. A phase noise of -75 dBc/Hz is observed at a 1 MHz frequency offset from the 14.21 GHz beat signal and a 5 dB reduction of the phase noise compared to the free-running condition is observed.

VI. Conclusion

In the past years, reports on microwave generation by using a DFL were mainly focused on very low phase noise [4] or large tunability [5]. However, there seems to be very little attention to one of the most crucial requirements of the generated carrier, namely its long-term frequency stability. Our OFLL clearly addresses this crucial requirement by achieving a frequency stability of $\sim 1\times 10^{-10}$ for averaging times ranging between 10 s and 1000 s and shows a loop response of 15 µs. A stable carrier of 14.21 GHz is observed with a phase noise of -75 dBc/Hz at 1 MHz frequency offset. Since our DFL has great potential for integration with generic silicon-based photonic platforms, it paves the way for microwave generation on a hybrid integration platform. An integrated OFLL will be less affected by the overall environmental noise because of its reduced footprint [16], thus promising an even higher stability.

REFERENCES

[1] S. Ayotte, A. Babin, P. Poulin, M. Poulin, A. Jeanneau, M. J. Picard, D. Poulin, C. A. Davidson, M. Aube, I. Alexandre, F. Costin, F. Pelletier, J. F. Cliche, and M. Têtu, "Laser synthesizer of the ALMA telescope: Design and performance," in *IEEE Topical Meeting on Microwave Photonics (MWP)*, 2010, pp. 249-252.

[2] J.-F. Cliche, B. Shillue, C. Latrasse, M. Tetu, and L. R. D'Addario, "A high-coherence high-stability laser for the photonic local oscillator distribution of the Atacama Large Millimeter Array," in *Proc. SPIE* Scotland, UK, 2004, pp. 1115-1126.

[3] M. R. H. Khan, D. A. I. Marpaung, M. Burla, C. G. H. Roeloffzen, E. H. Bernhardi, and R. M. de Ridder, "Investigation on the performance of an optically generated RF local oscillator signal in K_u-band DVB-S systems," in *General Assembly and Scientific Symposium, 2011 XXXth URSI*, 2011, pp. 1-4.

[4] G. Pillet, L. Morvan, M. Brunel, F. Bretenaker, D. Dolfi, M. Vallet, J. P. Huignard, and A. Le Floch, "Dual-frequency laser at 1.5 µm for optical distribution and generation of high-purity microwave signals " *J. Lightwave Technol.,* vol. 26, pp. 2764-2773, Jul-Aug 2008.

[5] X. He, X. Fang, C. Liao, D. N. Wang, and J. Sun, "A tunable and switchable single-longitudinal-mode dual-wavelength fiber laser with a simple linear cavity," *Opt. Express,* vol. 17, pp. 21773-21781, 2009.

[6] S. Camatel and V. Ferrero, "Phase noise power spectral density measurement of narrow linewidth CW lasers using an optical phase-locked loop," *IEEE Photon. Technol. Lett.,* vol. 18, pp. 2529-2531, 2006.

[7] F. Friederich, G. Schuricht, A. Deninger, F. Lison, G. Spickermann, P. Haring Bolívar, and H. G. Roskos, "Phase-locking of the beat signal of two distributed-feedback diode lasers to oscillators working in the MHz to THz range," *Opt. Express,* vol. 18, pp. 8621-8629, 2010.

[8] M. Tani, O. Morikawa, S. Matsuura, and M. Hangyo, "Generation of terahertz radiation by photomixing with dual- and multiple-mode lasers," *Semicond. Sci. Technol.,* vol. 20, pp. S151-S163, Jul 2005.

[9] E. H. Bernhardi, M. R. H. Khan, C. G. H. Roeloffzen, H. A. G. M. van Wolferen, K. Wörhoff, R. M. de Ridder, and M. Pollnau, "Photonic generation of stable microwave signals from a dual-wavelength $Al_2O_3:Yb^{3+}$ distributed-feedback waveguide laser," *Opt. Lett.,* vol. 37, pp. 181-183, 2012.

[10] C. B. Svec and T. M. Shay, "Wide dynamic range Doppler-shift compensation for space-borne optical communications," *IEEE Photon. Technol. Lett.,* vol. 16, pp. 260-262, 2004.

[11] A. Chorti and M. Brookes, "A spectral model for RF oscillators with power-law phase noise," *IEEE Trans. on Cir. and Sys. I: Regular Papers,* vol. 53, pp. 1989-1999, 2006.

[12] A. Winter and P. Schmuser, "High-precision laser master oscillators for optical timing distribution systems in future light sources," in *Proc. of 10th European Particle Accelerator Conference*, Edinburgh, UK, 2006, p. 1064.

[13] E. H. Bernhardi, H. A. G. M. van Wolferen, L. Agazzi, M. R. H. Khan, C. G. H. Roeloffzen, K. Worhoff, M. Pollnau, and R. M. de Ridder, "Ultra-narrow-linewidth, single-frequency distributed feedback waveguide laser in $Al_2O_3:Er^{3+}$ on silicon," *Optics Letters,* vol. 35, pp. 2394-2396, Jul 2010.

[14] H. Y. Ryu, S. H. Lee, and H. S. Suh, "Widely tunable external cavity laser diode injection locked to an optical frequency comb," *IEEE Photon. Technol. Lett.,* vol. 22, pp. 1066-1068, 2010.

[15] D. R. Stephens, *Phase-locked loops for wireless communications: digital, analog, and optical implementations*: Kluwer Academic Publishers.

[16] J. S. Parker, A. Bhardwaj, P. R. A. Binetti, H. Yung-Jr, and L. A. Coldren, "Monolithically integrated gain-flattened ring mode-locked laser for comb-line generation," *IEEE Photon. Technol. Lett.,* vol. 24, pp. 131-133, 2012.