Dual-Wavelength $Al_2O_3:Yb^{3+}$ Distributed Feedback Waveguide Laser for Microwave Signal Generation

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Abstract—**We report a ytterbium-doped aluminum oxide dual-wavelength distributed feedback channel waveguide laser and its application in the photonic generation of stable microwave signals. A microwave signal at ∼15 GHz with a −3 dB width of 9 kHz was created via the heterodyne photodetection of the two laser wavelengths. The long-term (45 minutes) and short-term (10 ms) frequency stability of the microwave signal produced by the free-running laser is better than ±2.5 MHz and ±40 kHz respectively.**

***Keywords*– Distributed feedback (DFB) laser; dual-wavelength laser; microwave-photonics; Bragg gratings**

I. INTRODUCTION

The photonic generation of microwave or millimeter-wave signals has become an essential part of the emerging field of microwave photonics. Microwave signals are usually generated with complex and expensive electronic circuits and propagated along electrical distribution lines, which inherently have high propagation losses. Compared with the electronic solutions, photonic generation of microwaves has many advantages, such as high-frequency operation, low power consumption, low cost, as well as the distribution of the optical carrier signals over large distances via low loss, inexpensive optical fibers [1].

Optical heterodyning is an effective and promising method for photonic generation of microwave signals. One such optical heterodyning technique to generate microwave signals in the optical domain is to make use of a dual-wavelength laser, with the two wavelengths separated by the desired microwave frequency. Due to the fact that the two wavelengths are produced from the same laser cavity, the stability of the generated microwave can be much improved as compared with two individual free-running lasers, since any environmental perturbation will affect both wavelengths in a similar way.

In this work, we report a dual-wavelength distributed feedback (DFB) channel waveguide laser in ytterbium-doped aluminum oxide ($Al_2O_3:Yb^{3+}$). The free-running laser was used to generate a 9 kHz wide microwave beat signal at ∼15 GHz with a long-term (45 minutes) frequency- and power stability better than 2.5 MHz and 0.35 dB respectively.

II. FABRICATION

The DFB cavity consisted of a 1-cm-long uniform waveguide Bragg grating, which has been integrated with a 1-µm-thick and 2.5-µm-wide $Al_2O_3:Yb^{3+}$ ridge waveguide [2]. The waveguide layer was deposited on a thermally oxidized standard silicon wafer by means of reactive cosputtering [3]. The sputtering powers applied to the metallic targets were selected such that the resulting Yb^{3+} concentration in the waveguide was approximately 5.8×10^{20} cm^{-3}. The channel waveguides were defined by means of standard lithography and etched ~90 nm deep with a chlorine-based reactive ion etching process [4], after which a silicon dioxide cladding layer was deposited on top of the waveguides. An 80-nm-deep surface relief Bragg grating structure was fabricated in the top surface of the cladding layer by using laser interference lithography and reactive ion etching [2].

When two quarter-wavelength phase-shifts are induced in such a uniform waveguide Bragg grating, two resonance peaks appear in the transmission stop band of the device [5]. These two resonances share a common cavity, which consists of both the phase-shift regions. The wavelength spacing between the resonances depends on the spatial separation and the values of the respective phase-shifts. The required phase-shifts were induced via two sections with 2-mm-long adiabatic sinusoidal widening of the waveguide width [2].

When both phase-shifts are varied symmetrically from a quarter-wavelength phase-shift $\pi/2$, such that one has a value of $\pi/2 - \Delta\theta$ and the other $\pi/2 + \Delta\theta$, the two resonant wavelengths separate symmetrically from each other with respect to the Bragg wavelength. As the value of the phase detuning $\Delta\theta$ increases, the shorter wavelength oscillates more around the $\pi/2 - \Delta\theta$ phase shift, while the longer wavelength concentrates around the $\pi/2 + \Delta\theta$ phase shift, instead of both wavelengths concentrating equally around both phase-shift regions simultaneously, as in the case of $\Delta\theta = 0$. Since each longitudinal mode is being amplified mainly by separate sections of the active medium, the degree of longitudinal mode competition is reduced, which results in less fluctuations in the optical power, and consequently also less frequency fluctuations in the laser generated microwave signal.

III. CHARACTERIZATION

The laser was optically pumped by a 976 nm diode laser of which the light was launched into the waveguide via the 980 nm port of a wavelength-division-multiplexing (WDM) fiber which was butt-coupled to the chip, while the laser emission was collected through the 1030 nm port of the WDM

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fiber. The laser emission was sent to a 40 GHz photodetector which was connected to an electrical spectrum analyzer. The measured beat signal at 15.0426 GHz confirmed that the laser was operating on two longitudinal modes (Fig. 1).

The two sidebands which are visible on either side of the main microwave peak are produced by relaxation oscillations from the two respective longitudinal modes. The two relaxation–oscillation frequencies were used to calculate the Lamb's coupling constant, a value that indicates whether there exists weak ($C \approx 0$) or strong ($C \approx 1$) mode competition between the two oscillating wavelengths [6]. The calculated value of $C = 0.23$ indicates that the mode competition was rather weak, since each longitudinal mode was being amplified mostly by separate sections of the active medium.

The long-term frequency stability of the microwave beat signal was measured over a period of 45 minutes with a 100 ms interval. The standard deviation of the microwave frequency during this period was found to be 2.5 MHz, while the power of the microwave signal was stable within 0.35 dB. To investigate the short-term frequency stability, the microwave signal at the output of the photodiode was mixed with a high-purity, stable electrical reference signal with a subhertz linewidth. Since the reference signal was much narrower than the laser beat signal, mixing of the two signals produced a convoluted signal that was nearly identical in shape to the original microwave beat signal produced by the laser, but shifted to the kilohertz range, so that a time trace of this downconverted signal could be measured with an oscilloscope. A short-time Fourier transformation was performed on the time trace of the downconverted signal to obtain a spectrogram over a duration of 10 ms. The short-term frequency stability of the microwave signal during the 10 ms period was 40 kHz.

To determine the linewidth of the laser, a single temporal slice was extracted from a spectrogram with a frequency resolution of 8 kHz. This confirmed that the microwave signal produced by the laser was below 9.0 kHz, which implies an individual laser linewidth below 4.5 kHz (Fig. 2).

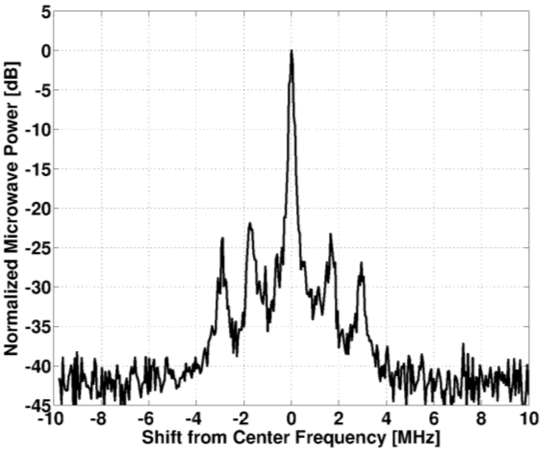

Figure 1. Electrical spectrum of the microwave beat signal centered at 15.0426 GHz, measured with a resolution bandwidth of 50 kHz.

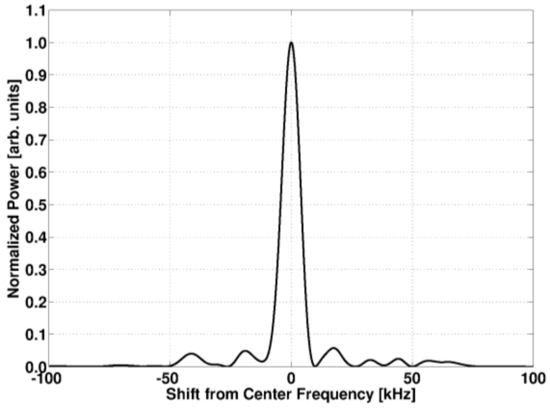

Figure 2. The spectrum which was extracted from a single temporal slice out of a spectrogram with an 8 kHz resolution. The -3 dB width of the microwave signal was below 9.0 kHz.

IV. SUMMARY

We have demonstrated a continuous wave dual-wavelength $Al_2O_3:Yb^{3+}$ DFB channel waveguide laser for the photonic generation of stable microwave signals. The narrowband microwave beat signal produced by the dual-wavelength laser was centered at ~15 GHz, with a frequency stability of ±2.5 MHz. This result emphasizes the great potential of using rare-earth-ion-doped monolithic waveguide lasers for the photonic generation of stable microwave signals.

REFERENCES

[1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," Nat. Photonics, vol. 1, pp. 319- 330, June 2007.

[2] 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, Jan. 2012.

[3] K. Wörhoff, J. D. B. Bradley, F. Ay, D. Geskus, T. P. Blauwendraat, and M. Pollnau, "Reliable low–cost fabrication of low–loss $Al_2O_3:Er^{3+}$ waveguides with 5.4–dB optical gain," IEEE J. Quantum Electron., vol. 45, pp. 454-461, May 2009.

[4] J. D. B. Bradley, F. Ay, K. Wörhoff, and M. Pollnau, "Fabrication of low–loss channel waveguides in Al_2O_3 and Y_2O_3 layers by inductively coupled plasma reactive ion etching," Appl. Phys. B, vol. 89, pp. 311-318, Oct. 2007.

[5] G. E. Villanueva, P. Pérez-Millán, J. Palací, J. L. Cruz, M. V. Andrés, and J. Martí, "Dual-Wavelength DFB Erbium-Doped Fiber Laser With Tunable Wavelength Spacing," IEEE Photon. Technol. Lett., vol. 22, pp. 254-256, Feb. 2010.

[6] M. Brunel, A. Amon, and M. Vallet, "Dual-polarization microchip laser at 1.53 μm," Opt. Lett., vol. 30, pp. 2418-2420, September 2005.