Photonic Generation of Microwave Signals Using Dual-Wavelength Distributed-Feedback Waveguide Lasers

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The fabrication and characterization of dual-wavelength distributed-feedback channel waveguide lasers in $Al_2O_3:Yb^{3+}$ are described. These integrated lasers are used to generate narrowband microwave signals, with frequencies ranging between 12.43 GHz and 23.2 GHz, via the heterodyne photodetection of the two optical waves emitted by each cavity. In particular, the frequency- and power stability of a 9-kHz-wide microwave signal generated at ~15 GHz are investigated. The long-term frequency stability of the microwave signal produced by the free-running laser is better than ± 2.5 MHz, while the power of the microwave signal is stable within ± 0.35 dB.

Introduction

The photonic generation of microwave or millimeter-wave signals has recently attracted much research interest due to its great application potential in satellite communication and phased array antenna systems, as well as broadband wireless and radio-over-fiber networks, radar, and sensor devices [1]. Microwave signals are conventionally generated with complex and expensive electronic circuits, after which they are distributed along electrical distribution lines, such as coaxial cables, which intrinsically have high propagation losses. Compared with the electronic solutions, photonic generation of microwaves has many advantages, such as high-speed operation, low power consumption, low cost, and the distribution of the optical carrier signals via low-loss, inexpensive optical fibers over large distances [2]. One particularly successful method of generating 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. An electrical beat signal is then generated at the output of a photodetector, with a frequency corresponding to the wavelength spacing of the two optical waves.

Here, we report a dual-wavelength distributed feedback (DFB) channel waveguide laser in ytterbium-doped aluminium oxide ($Al_2O_3:Yb^{3+}$). Operation of the laser is based on two localized quarter-wavelength phase shifts in a DFB cavity [3]. The free-running laser was used to generate a 9-kHz-wide microwave beat signal at ~15 GHz with a long-term frequency stability of ±2.5 MHz measured over a period of 45 min, while the power of the microwave signal was stable within ±0.35 dB.

Design and Operation Principle

The $Al_2O_3:Yb^{3+}$ waveguide layer with an Yb^{3+} concentration of 5.8×10^{20} cm^{-3} and a thickness of 1 μm was deposited onto an 8-μm-thick thermally oxidized standard silicon

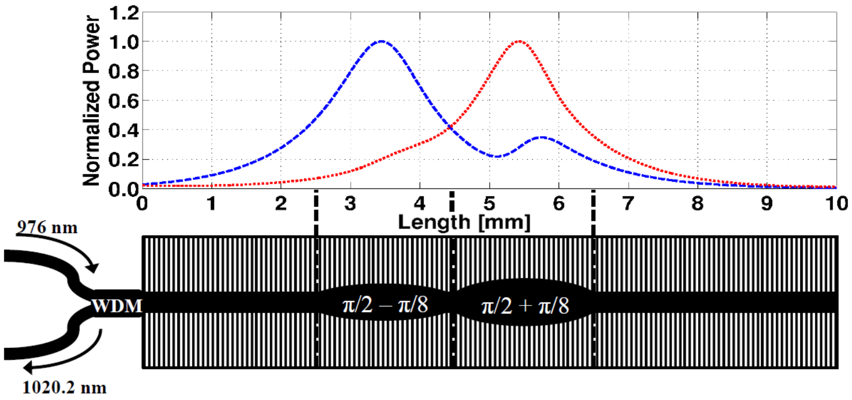

Figure 1. Schematic of the dual-wavelength DFB cavity, along with the calculated longitudinal field distribution of the two respective laser wavelengths.

wafer by means of reactive cosputtering [4]. The 2.5-µm-wide channel waveguides were defined with standard lithography and etched ~90 nm deep with a chlorine-based reactive ion etching process [5], after which laser interference lithography was used to define a Bragg grating structure with a length of 1 cm on the top surface of a SiO_2 cladding layer using laser interference lithography. The Bragg grating was etched ~80 nm deep with a CHF_3:O_2 reactive ion plasma.

When two phase shifts are induced in a uniform waveguide Bragg grating, two resonance peaks appear in the transmission stop band of the device [3]. The two resonances share a common cavity, which consists of both phase-shift regions. The wavelength spacing between these resonances depends on the spatial separation and values of the respective phase shifts. For two discrete quarter-wavelength phase shifts the frequency spacing between the two resonances is given by [6]

$$\Delta\nu = \frac{c}{8 n_{eff} \Delta L} \tag{1}$$

where c is the speed of light in vacuum, n_{eff} the effective refractive index of the guided mode, and ΔL the distance between the two phase shifts, resulting in $\Delta\nu$ = 11.7 GHz for n_{eff} = 1.6 and ΔL = 2 mm. However, 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 $\pi/2 + \Delta\theta$, then the two resonant wavelengths separate symmetrically from each other with respect to the Bragg wavelength [3]. In other words, the value of $\Delta\theta$ can be used to increase the frequency spacing between the two resonances as compared to the frequency spacing given by Eq. 1. To induce the required phase shifts in the waveguide Bragg grating, two sections with 2-mm-long adiabatic sinusoidal widening of the waveguide width were fabricated [7]. The two phase shifts were centered at 3.5 and 5.5 mm (as measured from the pumped end facet) and had values of $\pi/2 - \pi/8$ and $\pi/2 + \pi/8$, respectively. A schematic of the laser cavity, along with the calculated longitudinal field distribution of the two laser wavelengths, as calculated with the transfer-matrix method, is shown in Fig. 1.

Characterization

To characterize the laser, a (980/1030) ± 10-nm wavelength-division-multiplexing (WDM) fiber was butt coupled to the optical chip. The 976-nm diode pump light was launched into the waveguide via the 980-nm port of the WDM fiber, while the laser emission was collected through the 1030-nm port, which also contained a 22-dB isolator

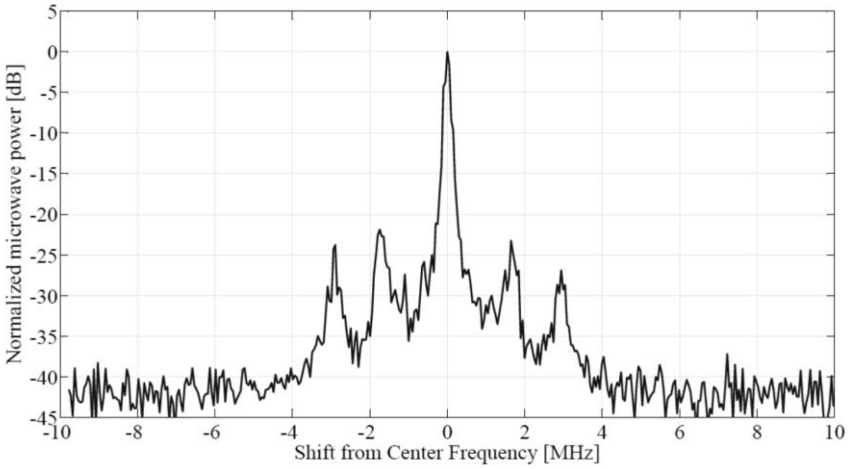

Figure 2. Electrical spectrum of the microwave beat signal centered at 15.0426 GHz measured with a resolution bandwidth of 50 kHz.

to prevent optical back reflections into the laser cavity. The laser emission was then sent to either an optical spectrum analyser (OSA), a power meter, or a 40-GHz photodetector (PD) connected to an electrical spectrum analyzer (ESA). The laser emission spectrum was centered at 1020.2 nm; however, the two individual laser emission peaks could not be resolved due to the limited 0.1-nm resolution of the OSA. To confirm that the laser was operating on two longitudinal modes, the laser output was measured with the PD and ESA, which confirmed a microwave beat signal at ~15 GHz (Fig. 2). The beat signal frequency implies a wavelength separation of 52 pm between the two individual longitudinal laser modes. The two sidebands on either side of the main microwave peak are produced by relaxation oscillations from the two respective longitudinal modes. The long-term frequency stability of the microwave beat signal was measured over a period of 45 min with a 100-ms interval. The standard deviation of the microwave frequency during this period was found to be ±2.5 MHz; see Fig. 3. During the same period, 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, which was produced by a microwave signal generator. This reference signal was set within a few hundred kilohertz of the ~15 GHz microwave beat signal produced by the laser. 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 with a frequency resolution of 20 kHz was performed on the time trace of the downconverted signal to obtain a spectrogram over a duration of 10 ms. By noting the center frequency of each spectrum in the spectrogram, the short-term frequency stability of the microwave signal during the 10-ms period was found to be 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 linewidth of the microwave signal produced by the laser was below 9.0 kHz, which implies an individual laser linewidth below 4.5 kHz, close to the 1.7 kHz previously demonstrated in an $Al_2O_3:Er^{3+}$ single-wavelength DFB laser [8].

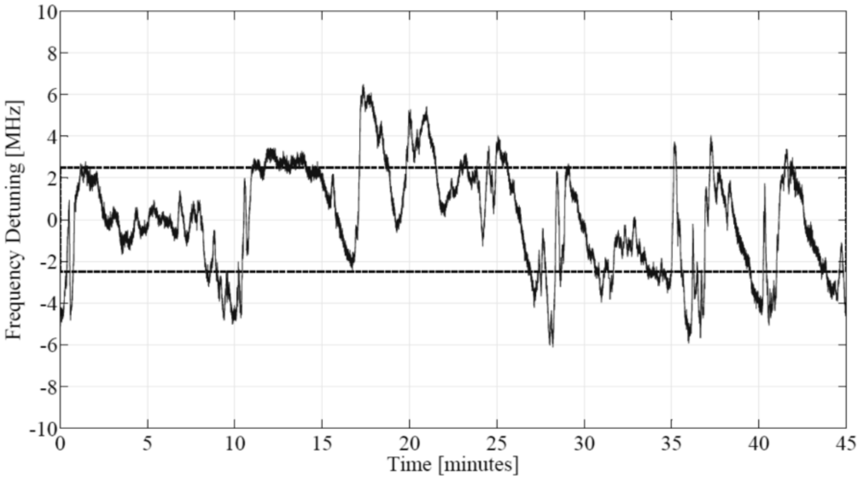

Figure 3. Measured frequency stability of the microwave signal during a period of 45 min where the standard deviation of the center frequency was 2.5 MHz (indicated by the horizontal black lines).

Summary

In conclusion, we have demonstrated an integrated $Al_2O_3:Yb^{3+}$ dual-wavelength DFB waveguide laser operating at 1020.2 nm. The laser was used to generate a stable, narrowband microwave signal at ~15 GHz. To our knowledge, this result represents the first dual-wavelength laser which has been fabricated on a silicon substrate. The stability performance and narrow line width of the free-running laser shows the great potential of using rare-earth-ion-doped monolithic waveguide lasers for the photonic generation of stable microwave signals.

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