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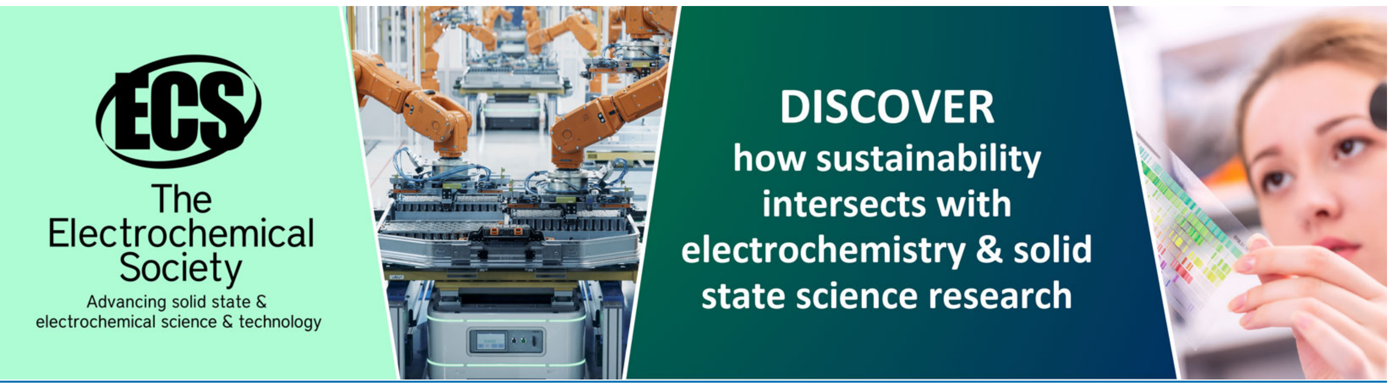

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Effect of coherent population trapping in a compact microfabricated Cs gas cell pumped by intra-cavity contacted VCSELs with rhomboidal oxide current aperture

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Abstract. Miniature laser source based on intracavity-contacted vertical-cavity surface-emitting laser with rhomboidal oxide current aperture was investigated for coherent population trapping (CPT) resonance excitation in microfabricated ^{133}Cs gas cell filled with Ne buffer gas under the pressure of 300 torr. The cell operation temperature was 90°C. The laser output power was 550 μW at bias current of 3.2 mA and 65°C. The short-term stability of $\sim 2.5 \cdot 10^{-11}$ at the measurement time of 1 sec was estimated from CPT resonance signal measurements.

Over recent years, the compact atomic clocks based on coherent population trapping (CPT) effect in alkali metal (rubidium ^{87}Rb or cesium ^{133}Cs) gas cells with laser pumping are subject of great interest [1]. The miniature (chip-scale level) atomic clock are usually pumped by semiconductor lasers which must satisfy several requirements: precise matching of the emission wavelength to the exploited necessary atomic line (usually D1 ^{87}Rb line or D1 ^{133}Cs line), lasing via fundamental mode with side-mode suppression ratio (SMSR) more than 20 dB, stable linear polarization with more than 15 dB orthogonal polarization suppression ratio (OPSR - peak-to-peak difference between the dominant mode and suppressed orthogonally polarized mode), emission linewidth less than 100 MHz, frequency modulation bandwidth more than 3.4/4.6 GHz for Rb/Cs cell at temperatures of 60-90°C, power consumption less than 5 mW [2]. Vertical-cavity surface-emitting lasers (VCSELs) are compact and energy-efficient laser sources, which can provide high-speed single-mode operation at elevated temperatures. However, the fabrication of polarization-stable single-mode VCSELs with low internal losses, narrow linewidth and reasonable series resistance is a big challenge in the case of conventional VCSEL design with current injection through doped distributed Bragg reflectors (DBR) [3]. In fact, the small lateral size of the current aperture is needed to provide stable fundamental transverse mode operation. However small aperture size leads to strong current-induced self-heating and gain suppression. The lack of asymmetry in conventional VCSELs with circular oxide aperture results in polarization instability. The mentioned drawbacks can be overcome by using the surface relief technique, but it requires complicated sub-micron lithography on non-planar surface with precise alignment of the oxide aperture and surface relief [4].

Recently, we have demonstrated an alternative approach based on advanced 850 nm-range VCSEL design with inracavity contacts (hereafter IC-VCSEL) [5-7]. The first unique feature of the proposed VCSEL design is the use of low-Q (several pairs of quarter-wavelength layers) DBRs between the intracavity contact layers and the cavity layer with light emitting media to redistribute the electromagnetic field intensity (standing wave profile). This leads to the reduction of the internal optical losses due to free carrier absorption and significantly increases the effective cavity length. The second feature is the specially designed AlAs/AlGaAs aperture layer optimized for the formation of the rhomboidal oxide current aperture using the anisotropy of the selective oxidation process. Rhomboidal oxide current aperture provides the reliable control of VCSEL linear polarization. The IC-VCSEL structures was optimized to obtain emission close to D1 ^{133}Cs line and was grown by molecular beam epitaxy. The details of the IC-VCSEL design and the device fabrication process can be found in [5, 8]. The characteristic size of the rhomboidal oxide current aperture is kept below 3 µm to provide single-mode operation. Selected IC-VCSEL chips have been mounted on the specially designed ceramic plates with integrated resistive heater (so-called IC-VCSEL-based laser source). Additionally, thermistor for temperature control and a microcoaxial RF-connector for VCSEL modulation were mounted on IC-VCSEL-based laser source.

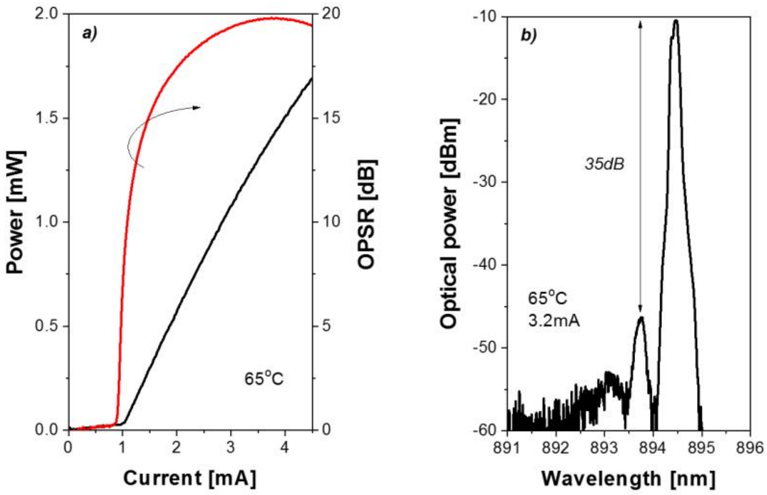

Figure 1. Static characteristics of the IC-VCSEL-based laser emitter: (a) output power and OPSR versus current at 65°C; (b) optical emission spectrum at 3.2 mA and 65°C

The light-current characteristic of IC-VCSEL-based laser source measured in CW regime at 65°C is shown in Figure 1.a. The threshold current of 1 mA and the slope efficiency of 0.5 W/A, allowed us to achieve the higher optical power at elevated temperature as compared to commercially available VCSELs for the D1 ^{133}Cs line [9]. Note that the IC-VCSEL structure was initially designed to provide high slope efficiency and output power but it can be easily adopted for relatively small output power (typical for compact atomic clock applications) by changing the mirror loss. The OPSR was calculated from the polarization-resolved light-current characteristics measured in the two polarization directions at 65°C. As shown in Figure 1.a, the OPSR exceeds 15 dB in the operation current range of 1.5-4.5 mA. Note that the orientation of the dominated polarization is strictly along the minor diagonal of the rhomboidal oxide aperture. Figure 1.b shows the optical emission spectrum at 65°C. The target wavelength of 894.6 nm is reached at current of 3.2 mA. The higher order transverse modes are suppressed by 35 dB relative to the fundamental transverse mode. According to the linewidth measurements by using a scanning Fabry-Perot interferometer, the emission linewidth does not exceed 60-70 MHz at current of 3.2 mA and temperature of 65°C.

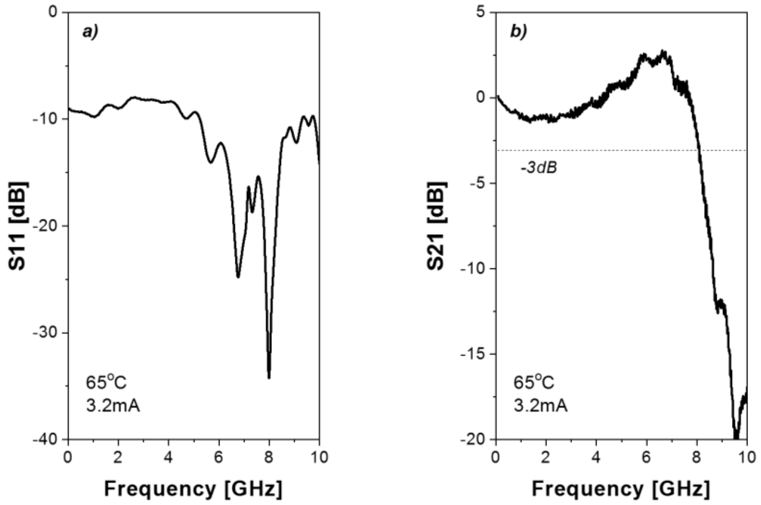

Figure 2. S-parameters of the IC-VCSEL-based laser source, measured at 3.2 mA and 65°C: (a) S11 – microwave reflection; (b) S21 – small signal modulation response

The optimal impedance matching between the RF modulation source with frequency of 4.596 GHz (required for CPT effect) and IC-VCSEL-based laser source is important to minimize power consumption and improve operation stability. Figure 2.a shows the module of S_{11}–parameter of the IC-VCSEL-based laser source measured in the 0.1 - 10 GHz frequency range. The absolute value of S_{11} is less than -8 dB in the range of 2 - 6 dB, which allows effective modulation by relatively low power microwave signal. According to small-signal analysis, the -3 dB modulation bandwidth of the VCSEL-based laser source reaches about 7 GHz at 2.5 mA with a modulation current efficiency factor (MCEF) more than 5 GHz·mA$^{-1/2}$, and then saturates at 8 GHz for higher currents. Figure 2.b shows the small-signal modulation response curve at the bias current of 3.2mA with corresponding -3 dB modulation bandwidth of about 8 GHz.

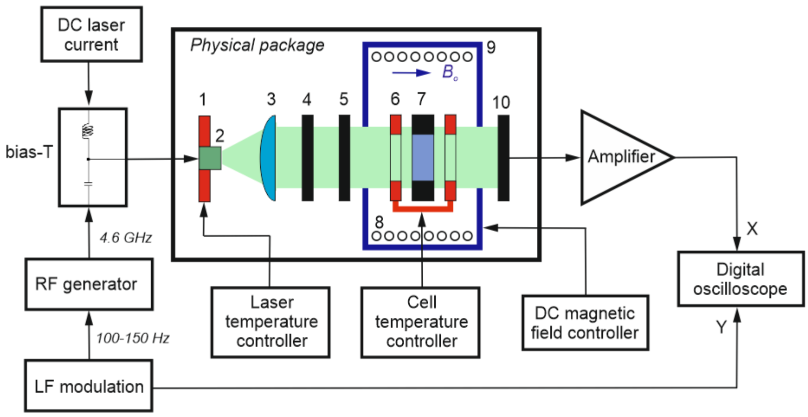

Figure 3. Schematic illustration of the experimental setup for measuring CPT resonance: 1 – laser heater, 2 – VCSEL, 3 – AR-coated lens, 4 – ND-filter, 5 – λ/4 waveplate, 6 – cell heater, 7 – microfabricated Cs cell, 8 – magnetic coil, 9 – μ-metal shield, 10 – PD

We used our IC-VCSEL laser sources for excitation of CPT resonance in compact microfabricated ^{133}Cs gas cell. The scheme of experimental setup is shown in Figure 3. It was successfully used in CPT experiments with ^{87}Rb glass-blown cells pumped by extended cavity diode laser Toptica DL100 with electro-optical modulator [10-11]. An important feature of this experimental setup is the compact design of a physical package (the so-called quantum discriminator) which consists of replaceable gas cell module and laser source module.

Instead of conventional glass gas cells fabricated by glass-blowing techniques or focused CO_2 laser we used the microfabricated silicon gas cells filled with Cs gas and pure Ne buffer gas. The gas cells were manufactured using an integrated technology [12]. Fabrication process starts from silicon wafer through etching to create two rectangular chambers (technological chamber and probe chamber) connected by filtration channels with the following anodic bonding of first glass window to the bottom side of the silicon chip. Next step is filling the technological chamber by microtablets with Cs isotope salt, anodic bonding of the second glass window to the face side of the silicon chip under a buffer gas atmosphere to completely seal the cell. The final step is heating the technological chamber by IR-laser through the glass window to generate Cs gas that moves to the probe chamber via filtration channels [13-14].

The resistive heater and thermistor of the IC-VCSEL-based laser source are connected in a feedback loop via laser temperature controller to tune the VCSEL wavelength to D1 ^{133}Cs line. At first, the diverging VCSEL beam is collimated by lens with AR coatings and attenuated by neutral density filter. Then the parallel laser beam with diameter of about 2 mm passes a quarter-wave plate, which turn the linearly polarized light into circular polarized one, and enters into the probe chamber of the microfabricated gas cell, where the light interacts with the Cs atoms gas. Finally, the light transmitted through the cell is detected by a Si PIN photodiode. The gas cell is surrounded by two ceramic plates with integrated bifilar heater based on non-magnetic metals, which are placed in a feedback loop via cell temperature controller. To split the Zeeman sublevels of the ground and excited states, the microfabricated Cs gas cell is placed inside the magnetic coil with magnetic field of about 10 μT parallel to the optical axis. The gas cell module is surrounded by a cylindrical μ–metal shield with the diameter of 4 cm and the length of 5 cm. The physical package has a total volume of 120 cm^3 and is realized in the modular design, which enables the fast replacement of the individual elements.

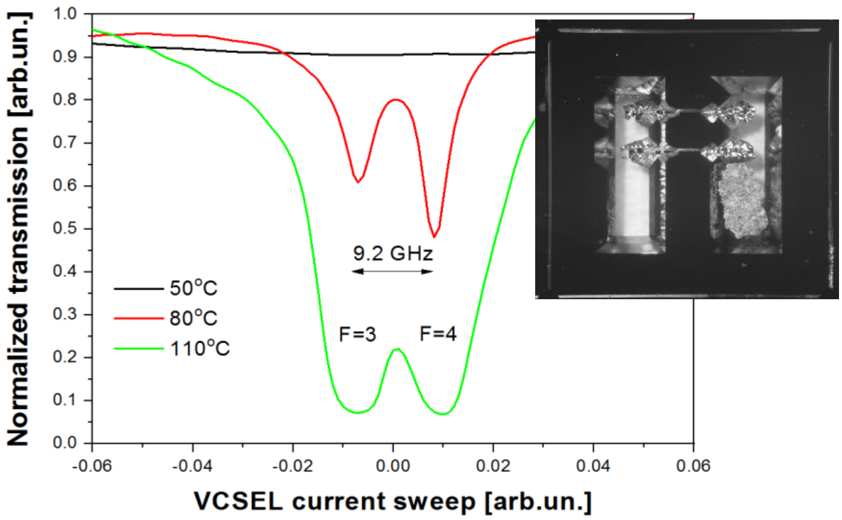

Figure 4. D1 ^{133}Cs absorption lines observed when transmitting the light of the IC-VCSEL through the microfabricated Cs gas cell at different cell temperature. Zero current detuning nearly corresponds D1 133Cs line. Inset: the optical microscopy image of the cell.

The gas cell employed in this experiments has the probe chamber with a rectangular cross section, 4 mm × 1.5 mm, and the optical path length of 600 μm for transmitted light (see inset in Fig.4). The cell contains cesium gas and Ne buffer gas under the pressure of 300 torr. Figure 4 shows the normalized optical absorption spectrum as the laser frequency is swept by changing its DC bias current (due to self-heating effect) near the D1 ^{133}Cs line. The two absorption lines are clearly observed at temperature above 60°C and can be associated with the ground state hyperfine splitting in cesium (F=3, F=4) separated by 9.192 GHz. Note that the coarse step of the sweep and/or inhomogeneous line broadening due to collisions between cesium and buffer gas atoms in case of high gas pressure limits the resolution of the D1 ^{133}Cs transitions. The strongest absorption was revealed at temperature more than 100°C, making it difficult to fine-tune the IC-VCSEL wavelength to D1 ^{133}Cs line. The optimal temperature for such microfabricated Cs gas cell is in range of 80-90°C.

RF generator and bias-tee are used to modulate the IC-VCSEL-based laser source with RF power of -3 dBm at half the frequency of the ground-state splitting to create the two frequency modulation sidebands at ± 4.596GHz from the carrier optical frequency of 335 THz (894,3 nm). It will enhance the light transmitting through the cell at carrier optical frequency (CPT resonance). By scanning the modulation frequency with a small-amplitude periodic waveform (LF generator) across the half of resonant frequency of hyperfine transition of the ground state in ^{133}Cs (1/2 · 9.192 = 4.596 GHz), CPT resonance can be detected in the DC transmitted light. The amplified photodiode signal is measured and averaged by a digital storage oscilloscope, which is synchronized with LF generator.

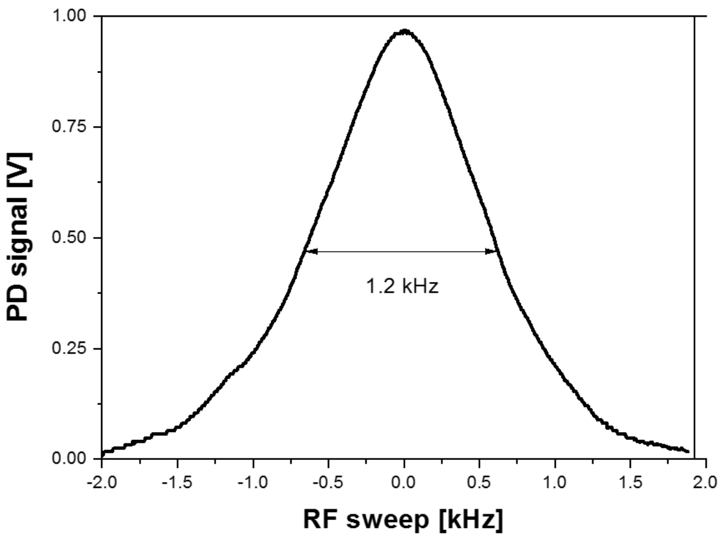

Figure 5. CPT resonance signal versus the sweep in microwave modulation frequency across the half of resonant frequency of hyperfine transition of the ground state in ^{133}Cs atoms, measured on the D1 133Cs line in the microfabricated Cs gas cell at 90°C.

Figure 5 shows a typical photodiode signal versus modulation frequency. The cell is stabilized at operating temperature of 90°C and illuminated with optical power of about 130 μW in beam aperture of 2 mm^2 (VCSEL output power of 550 μW at 3.2 mA and 65°C). The estimated linewidth of the CPT resonance is 1.2 kHz. The short-term stability of atomic frequency standard can be estimated as [15]:

$$\sigma(t) = [(S/N)_{1\mathrm{Hz}} \cdot Q]^{-1} \cdot t^{-1/2},$$

where Q is – the Q-factor of the atomic resonance equal to the ratio of the resonance frequency to the resonance linewidth, $(S/N)_{1\mathrm{Hz}}$ – signal-to-noise ratio of the detected signal measured in a 1 Hz bandwidth at the modulation frequency, t – the measurement time. The actual value of signal-to-noise ratio is about 10^4. Hence the short-term stability of $\sim 2.5\cdot 10^{-11}$ at the measurement time of 1 sec can be obtained for the developed microfabricated Cs gas cell and IC-VCSEL laser source.

According to the entire set of achieved characteristics, the developed single-mode polarization-stable IC-VCSELs with rhomboidal oxide current aperture in combination with microfabricated Cs gas cells are potentially suitable for use in compact atomic clocks based on CPT effect. Moreover designed IC-VCSELs can be promising for various optical spectroscopy application requiring narrow optical emission lines and miniature magnetometers.

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