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Quantum dot laser two-state self-mixing velocimetry: Simulation and experiment

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Abstract:
Compact two-state laser self-mixing is demonstrated. A Doppler signal, originating from the two-state interaction, yields the potential of high-velocity detection. Simulations verify the results and identify the quantum-dot-states carrier coupling as the relevant mechanism for the Doppler signal generation.

OCIS codes: (140.5960) Semiconductor lasers; (280.4788) Optical sensing and sensors; (280.3340) Laser Doppler velocimetry.

1. Introduction

Over the past years, single-mode semiconductor laser self-mixing interferometry (SMI) has established a wide range of metrology applications including velocimetry (SMV) [1-2]. In SMI, the laser irradiates a remote target and a small fraction of scattered coherent light re-enters the laser cavity causing a modulation of the laser field in the cavity both in frequency and amplitude, depending on the phase of the backscattered light. The SMI signal contains all information about the target motion along the optical axis without ambiguity [3]. In order to access high target velocities typically resulting in frequencies up to the GHz range, the need for fast and expensive detection systems complicates substantially the SMV concepts. In this paper, we report on a novel approach to avoid these restrictions by exploiting an additional Doppler signal generated by a single-chip two-mode quantum dot (QD) semiconductor laser which emits continuous-wave (CW) ground-state (GS) and excited-state (ES) emission at λ_{GS} = 1245 nm and λ_{ES} = 1175 nm, respectively. In addition to the expected two Doppler signals, originating from the GS and ES, a third Doppler signal originates from the coupling of the QD states. This third Doppler signal can be described by a synthetic wavelength $\lambda_s = \lambda_{GS}\lambda_{ES}/|\lambda_{GS}-\lambda_{ES}|$. Besides a perfect beam overlap of GS and ES, the presented concept bears the particularly attractive potential to access unprecedented high remote target velocities with a relatively low experimental effort as compared to [4].

2. Experimental two-state SMV set-up

Stable CW two-state emission is realized with a 2 mm long homogeneously pumped two-section QD laser with 5 identical InAs QD layers embedded in InGaAs Quantum Wells. Sole ES emission is obtained at room temperature operation while stable two-state emission is obtained by operating the laser at 16 °C due to reduced losses [5]. Spectral selectivity is obtained by grating feedback whereby the coupling strengths are individually adapted by two variable attenuators in the double Littrow configuration (Fig. 1). The signal of the remote target that is mounted on top of a high precision motorized linear translation stage is investigated the following up to a velocity of 4.5mm/s.

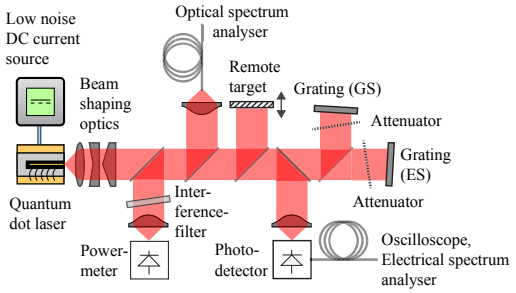

Fig. 1 Experimental set-up applied to demonstrate versatile synthetic-wavelength SMV with a dual-state QD laser.

3. Experimental and simulation results

The experimentally realized two-state emission is depicted in the optical spectrum shown in Fig. 2. A spectral QD state separation of ≈ 72.5 nm is indicated corresponding to λ_s = 21 µm. The first indications of λ_s can already been viewed in the measured time-domain SMV signal as shown in Fig. 3 where a clear beat envelope with a frequency corresponding to λ_s is observed. Besides its velocity, the target displacement can also be extracted from Fig. 3 by fringe counting. The third doppler signal is evident after low-pass filtering the time trace (red plot in Fig. 3). The

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obtained frequency-domain SMV signal is depicted in Fig. 4 for a constant target velocity of 3 mm/s. A broad signature at a center frequency of f_{GS+ES} = 4.98 kHz with a -6dB-width of Δf_{GS+ES} = 860 Hz constitutes the overlapping of GS and ES SMV signals. A considerably narrow peak at a center frequency f_s = 295 Hz with a -6dB-width of only Δf_s = 13 Hz is evident, clearly representing the beat frequency of λ_s. The target velocity is estimated to be v = 2.96 mm/s resulting in a measurement error of λ_s of only 1.3 %.

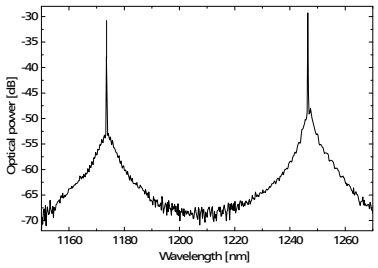

Fig. 2 Experiment: Simultaneous GS and ES emission at 16°C and a gain injection current of 54.9 mA indicating stable two-state emission.

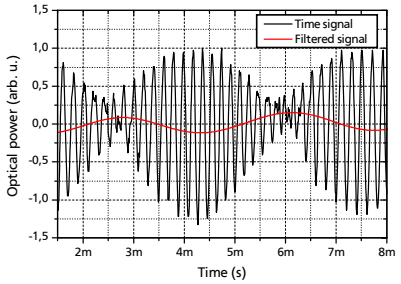

Fig. 3 Experiment: Oscilloscope time trace (unidirectional target movement) displaying the interference signal and beat envelope corresponding to λ_s. Red line: low-pass filtered time signal.

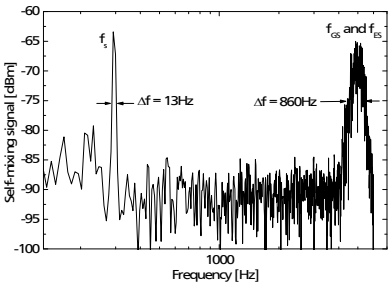

Fig. 4 Experiment: Radio-frequency trace (target velocity of 3 mm/s) indicating the narrow microwave Doppler beat signal originating from λ_s as well as the Doppler signal f_{GS+ES} of GS and ES.a

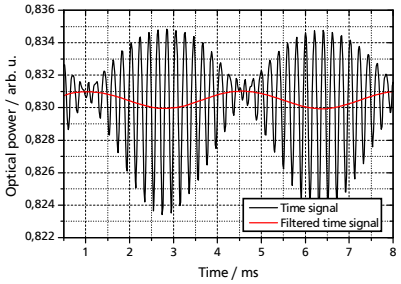

Fig. 5 Simulation: Time-trace. Red line: low-pass filtered time signal corresponding to the experimental conditions depicted in Fig. 3.

Fig. 5 depicts the simulation results based on [6]. Simulations explain the origin of the novel Doppler beat signal (red trace in Fig. 5) based on the coupling of the GS and ES photons by means of the carrier relaxation and blocking.

4. Conclusion

We report a new two-state SMV concept by exploiting the unique advantages of a QD laser to obtain a third Doppler signal with a synthetic wavelength of 21 µm. In the RF domain, we verify this beat signal as a robust narrow peak with a frequency 17 times smaller than the single-mode SMI frequency and an -6 dB width of only 13 Hz and explain its origin by means of simulations. These achievements demonstrate the first application of a compact QD laser source exploiting the QD specific two-state emission.

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