Generation of non-classical light using semiconductor quantum dot lasers

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***Abstract*—With a suppressed-pump-noise configuration, we have observed broadband amplitude-squeezed states of light generated from a 1310-nm distributed feedback quantum dot laser at room temperature.**

***Index Terms*—quantum dot lasers, squeezed states of light**

I. Introduction

A semiconductor laser operating far above the threshold can emit a nearly coherent state with shot-noise-limited emission when measured by a photodiode [1]. However, the possibility of producing non-classical or squeezed states of light has also led to numerous studies in quantum optics over the last decades. In such states, the fundamental quantum noise of two quadrature components is redistributed according to the Heisenberg uncertainty principle. Precisely, squeezed states have fewer fluctuations in one quadrature component than a coherent state at the expense of enhanced fluctuations in the other [2] as shown in Fig. 1. Yamamoto *et al.* [3], [4] proposed achieving amplitude-squeezed light through constant-current-driven semiconductor lasers. In this scheme, the low-frequency intensity noise of the laser can be reduced below the shot noise level at a high pump rate (usually several times the threshold current) through a noise-suppressed pumping configuration. This method is considered promising in terms of wavelength tunability, broad squeezing bandwidth, high output power, and compactness of laser diodes. Moreover, this scheme can also be integrated into a silicon photonic chip and be used to design novel quantum key distribution communications channels relying on using a compact squeezer.

In recent years, semiconductor quantum dot (QD) lasers have been one of the best practical examples of emerging nanotechnologies thanks to the atom-like discrete energy levels. The 3-dimensional spatial quantization leads to ultimate carrier confinement which enables high-performance photonic devices along with possible additional quantum phenomena [5]. QD lasers have many important benefits over conventional laser diodes like quantum well lasers and then can be proposed as a promising source for amplitude-squeezed light. In this work, we investigate the intensity noise of a 1.3 μm distributed feedback (DFB) quantum dot laser at room temperature. Based on the measurement of a balanced homodyne detection, we present the first demonstration of amplitude squeezing in quantum dot lasers: 0.3 dB below the shot noise level (SNL) over 4 GHz of noise intensity spectrum is obtained at room temperature using the suppressed-pump-noise configuration. We believe that this result can offer huge advantages in various quantum applications, including quantum metrology and continuous-variable quantum key distribution.

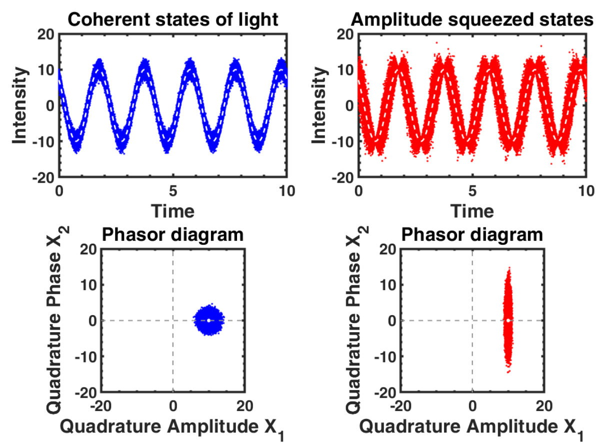

Fig. 1. The heuristic time series and noise distribution of coherent states (blue) and amplitude-squeezed states (red). A quantum electric field operator is $\hat{E}_x(z,t) = 2E_0 \sin(kz)(\hat{X}_1 \cos\omega t + \hat{X}_2 \sin\omega t)$, where $\hat{X}_1$ and $\hat{X}_2$ are Hermitian quadrature amplitude and phase operators that satisfy the minimum-uncertainty product as $< (\Delta\hat{X}_1)^2 >< (\Delta\hat{X}_2)^2 >$ = 1/16. Amplitude-squeezed states have less projection area on the X_1 axis.

The device used in our experiment is a QD DFB laser, whose active region is grown from InAs QDs on (100) GaAs substrate, and details can be found in Ref [6]. The threshold current I_{th} at 20 °C is 9 mA. The stable single-longitudinal-mode operation in 1310 nm can be obtained for a broad range of pump currents. The experimental setup for amplitude squeezing is shown in Fig. 2. The laser is pumped with a precision, quiet pump (ILX Lightwave LDX-3620), and the output beam is divided into two paths by a 50/50 beamsplitter after an optical isolator, namely an unknown signal and a local oscillator (LO). The LO acts as a phase reference and its phase relation to the signal is shifted via an optical delay

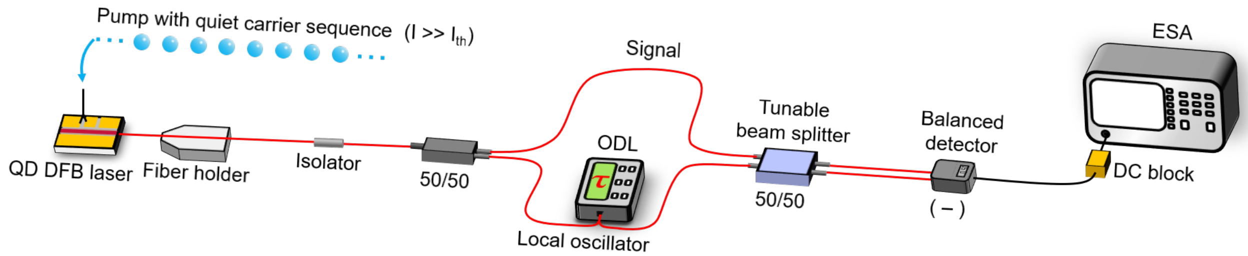

Fig. 2. Experimental setup for measurement of the amplitude noise spectrum in a DFB QD laser. ODL means optical delay line.

line to distinguish between the quadratures. Then two paths combine into an exact 50/50 beamsplitter and are connected to two identical photodiodes to guarantee optical balancing. The difference between two photocurrent noises is amplified by an electronic amplifier and is subsequently measured with an electrical spectrum analyzer (ESA) to obtain the intensity noise spectrum. This is the usual technique to distinguish between quantum noise and classical noise since classical noise contributions in the two paths are correlated and can cancel each other which is not the case for the quantum noise [7]. The shot noise level (SNL) or so-called standard quantum limit (SQL) is calibrated by replacing the quiet pump with the normal pump (Keithley 2400) and also using a vacuum LO. By doing so, the balanced detection can suppress the excess intensity noise over 20 dB. The RF frequency spectrum of the subtracted photocurrent remains unchanged when the pump current varies and thus we verify this is truly the quantum-mechanical noise limit.

Fig. 3 shows the measured noise power spectral density for the laser biased at 50 mA and the amplitude squeezing (blue curve) and anti-squeezing (red curve) are compared with the calibrated SQL (black dashed curve). In fact, the measured variance of the photocurrent fluctuations is a weighted combination of the variance of the fluctuations in the two quadratures. And the projection angle of two quadrature components can be selected by scanning the relative phase difference ϕ_{LO} between the signal and LO (i.e., altering the optical delay time). For example, for $\phi_{LO} = 0$, the variance in the quadrature amplitude X_1 is measured while for $\phi_{LO} = \pi/2$ the variance in the quadrature phase, X_2 is measured as explained in Fig. 1. Therefore, the spectrum of squeezing is found when the projection angle is adjusted to the maximum squeezing direction X_1 and the anti-squeezing is the minimum X_2. It is clear that the photocurrent spectrum between 1 GHz and 5 GHz is reduced well below the SQL. The maximum noise reduction occurs at the single frequency near 4.8 GHz and is 0.3 dB (6.7%) in power below the SQL, and the averaged noise reduction in the whole squeezing bandwidth is 0.2 dB. Before 500 MHz, the squeezing spectrum is strongly affected by the Flicker (1/f) noise.

In conclusion, we observed the broadest bandwidth for quantum noise reduction below SQL in semiconductor lasers. To our knowledge, the best performance in the previous experiment was 1.1 GHz at 77 K [8]. The QD lasers have demonstrated a high-performance squeezing light at room temperature, driving its application in silicon-based integrated optical quantum chips.

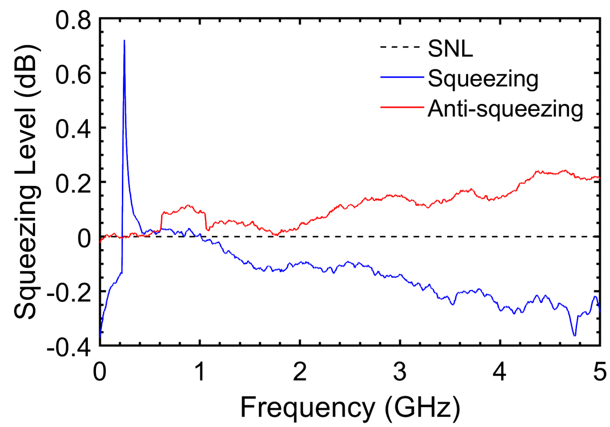

Fig. 3. Measured noise spectrum normalized by SQL at 50 mA.

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