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Generation of Intensity Squeezing in Laser Diodes by Weak External Cavity Feedback *

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We report the generation of intensity squeezing in a single-mode laser diode by weak external cavity feedback. The measurable squeezing of the output beam is 4.7%, corrected to 8.9% for the actual squeezing. This proves that intensity squeezing can be obtained by weak feedback.

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The generation of intensity squeezing in laser diodes has been extensively studied since its first realization by Yamamoto *et al.* in their 1987 experiment.[1] It has now become a very important area in quantum optics. Ideal intensity squeezing which produces the Fock state, is known to have the largest capability in optical communication and has great potential use. Because of its simplicity and reliability, compared to other processes such as optical parametric conversion, much research has focused on the generation of intensity squeezing in laser diodes. However, intensity squeezing in laser diodes can be obtained usually only at very low temperatures. The best result accomplished by Richardson *et al.*[2] in 1991 was 8.3 dB, which was obtained at 66 K. In 1993, it was shown by Steel *et al.*[3] that some line-narrowing techniques, such as grating feedback or injection-locking, greatly helped in the noise reduction, and intensity squeezing can be obtained at room temperature. By using grating feedback, 2.3 dB squeezing was obtained by one of the authors of this letter and others.[4] However, the large losses with grating feedback reduce the output squeezing and one cannot bring the high quantum efficiency of semiconductor lasers into full play. Finding an ideal way to realize intensity squeezing is still a problem. In 1994, Kitching *et al.*[5] proved theoretically that intensity squeezing can be achieved through weak external cavity feedback when one chooses the proper phase and intensity of the feedback light. In this letter we report the experimental realization of intensity squeezing in a single mode laser diode through weak feedback. By controlling the phase of the feedback light with a piezoelectric transducer, nearly 9% of squeezing was obtained over a long time. This result can be improved by reducing the total beam transmission loss.

The laser diodes used are index-guided quantum well GaAlAs laser diodes (Spectra Diode model SDL-5411-G1) operating at 850 nm. The rear facet reflection coefficient is 95%, and the front facet is antireflection coated with a reflection coefficient of about 4%. The free-running laser diodes have a threshold of 20 mA and intensity noise of usually 2–5 dB above the shot noise level (SNL). The whole experimental setup is shown in Fig. 1. LD is a laser diode which is driven by a high resolution laser diode driver (the fluctuation of the driving current is less than 10 nA) and temperature is stabilized around room temperature with 0.01°C fluctuation. L1 is a collimating lens of focal length $f = 7.5$ mm placed in front of the output facet of the diode. BS1 is a beamsplitter with a reflection coefficient of 10%. M is a plane mirror with a reflection coefficient of 15% and is glued on a piezoelectric transducer (PZT) which is mounted on a finely oriented mirror mount. The feedback coefficient in the system due to BS1 and M is less than 0.15%. P is a pair of anamorphic prisms used to convert the laser beam shape to near-circular. OI is the optical isolator system. Through a half-wave plate (HP) and another lens L2, the beam arrives at the balanced detector[6] which consists of a beamsplitter BS2 and two photodiodes. The beam going to BS2 is split into two equal parts. Each output of the beamsplitter is sent into a high efficiency (81%) photodiode (EG&G model FND 100). The dc parts of the photodiode current are filtered out while the ac parts are amplified using 20 MHz bandwidth amplifiers. The outputs of amplifiers, proportional to the noise signals, are either

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subtracted or added by a rf +/− power combiner. When set on the difference position, the circuit gives a signal proportional to the shot noïse, while in the sum position, it gives the full intensity noise of the beam impinging on the beamsplitter. The output of the +/− power combiner is sent to a spectrum analyzer (SA) and noise spectra are recorded for the sum and the difference signals. The electronic noise is then subtracted from each recording. In addition, we split a tiny part of the light (about 1%) before the HP and monitor the laser mode with a Fabry-Perot (F-P) cavity and photodetector D4 throughout the whole experiment to check that the laser operates in single mode.

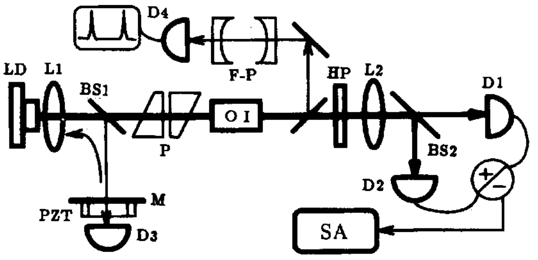

Fig. 1. Experimental setup.

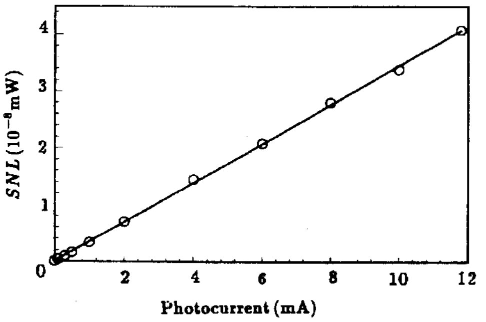

Fig. 2. Shot noise of the white light source vs the photocurrent. The analysis frequency is 8 MHz.

Before the experiment, the consistency between the shot noise of a laser diode measured in this way and the noise of a white light source was carefully checked. The same photocurrent from the white light source and the laser diode should have the same shot noise level. Figure 2 is the shot noise from the white light source vs the photocurrent at an analysis frequency 8 MHz. What we do is to focus the light from an incandescent bulb on the photodetector FND 100 and measure its noise directly with a spectrum analyser at different photocurrents. The focused beam size is about 5 mm^2 which is just the area of the sensitive surface of the photodetector. The measurements show that the photodiodes and amplifiers are linear up to 12 mA of the photocurrent. Because the white light source was not very bright we could not check when the photodiode and amplifier saturated. However, the operating photocurrent in our experiment for each detector is much lower than 12 mA and so is always in the linear response range.

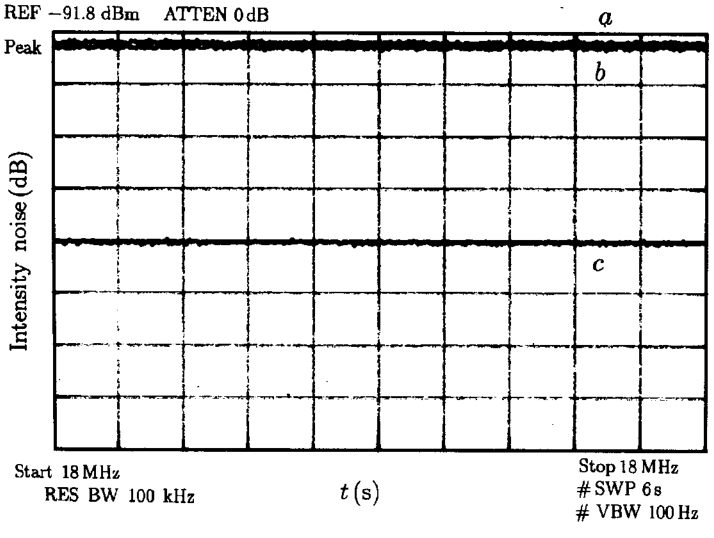

Fig. 3. Intensity noise of the laser diode: *a*: SNL; *b*: intensity noise level; *c*: electronic noise level. The vertical scale is 1 dB/div.

First, one must adjust the lens L1 and the prisms to collimate and shape the beam, then align the optical isolator to get single mode operation. The laser diode threshold shift can be monitored by scanning the driving current. The mirror M is aligned to get the maximum threshold shift. By changing the dc voltage bias on the PZT, one can control the phase of the feedback light, find the minimum noise of the intensity and measure it.

The laser diode operates at 80.30 mA, producing 8 mA of dc photocurrent in each photodiode, so the overall quantum efficiency is about 20%. Figure 3 shows the result, where the analysis frequency is 18 MHz, the resolution bandwidth 100 kHz and the video filter bandwidth 100 Hz. The upper trace *a* is SNL; the middle trace *b* is the intensity noise level and the lower trace *c* is the electronic noise level. The scale is 2 dB/div. Figure 4 is the same as Fig. 3 but with a scale of 0.1 dB/div., so *a* and *b* in Fig. 3 are amplified and it is clear that the intensity noise *b* is lower than the SNL *a*. When corrected for the electronic noise, the intensity noise is 0.21 dB lower than the SNL, which corresponds to 4.7% of squeezing. After taking into account the total transmission efficiency of 65% and the photodiode quantum efficiency (81%), the intensity squeezing of the output beam is actually 8.9%. We also measured the noise from 9 kHz to 20 MHz and found that squeezing exists from about 10 to 20 MHz. For higher frequency, the measurement is limited by the amplifier. Because the squeezing is not high, it is difficult to display the noise curve over a wide frequency range with a large vertical scale on the spectrum analyser, and here we show the result at 18 MHz in Figs. 3 and 4.

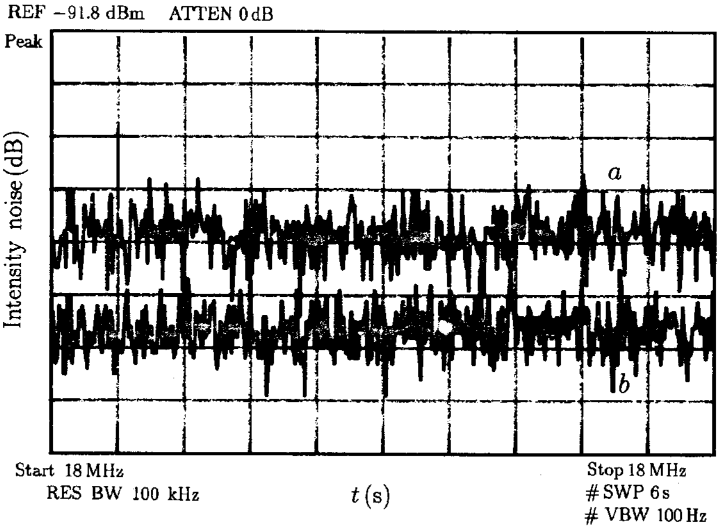

Fig. 4. Intensity noise of the laser diode. All the parameters are the same as in Fig. 3 except that the vertical scale is 0.1 dB/div. *a*: SNL; *b*: intensity noise level.

In conclusion, intensity squeezing by weak external cavity feedback in a single mode laser diode has been obtained. Although the squeezing is not so high, our method is simple and reliable. The weak feedback overcomes the large loss in grating feedback. The overall quantum efficiency is 20% but we obtained only 4.7% of squeezing, which means that there are some factors, such as noise from the power supply, noise due to losses and spontaneous emission, etc. The results should be improved by optimizing the amount of feedback (here the amount of feedback is fixed) and by reducing the whole system losses. Our results verify Kitching's prediction that squeezing can be achieved by weak feedback.

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