Generation of Tunable Amplitude-Squeezed Light by Injection Locking of a Laser Diode *

WANG Jun-Min(王军民), HE Ling-Xiang(贺凌翔), ZHANG Tian-Cai(张天才),
XIE Chang-De(谢常德), PENG Kun-Chi (彭堃墀)
Institute of Opto-electronics, Shanxi University, Taiyuan 030006

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Tunable amplitude squeezing around the D_2 line of cesium has been experimentally accomplished at room temperature in a quantum-well laser diode with light injection from a single-mode distributed Bragg-Reflector laser diode. While the master laser frequency is tuned, amplitude squeezing of the output light from the slave laser can be maintained at about 0.9 dB throughout a tunable range of ~1.7 GHz around the cesium D_2 line.

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Amplitude squeezing of a laser diode was predicted by Yamamoto *et al.*[1] in 1986 and first realized experimentally by themselves in 1987.[2] Up to now there are various methods which can realize amplitude squeezing of a laser diode, such as high-impedance constant-current driving,[2-4] cooling in a cryostat,[5,6] external optical feedback[7-10] and injection-locking.[11-14] Also there is some calculation and application about the squeezing state in a viewpoint of the theoretical analysis.[15-21] All these schemes have different influences on the reduction of amplitude noise. Compared with other methods, injection locking can not only provide single-mode amplitude-squeezed lights, but also produce phase coherence between the master laser and the slave laser.[12] Amplitude squeezed light obtained with injection locking can be used in the interferometer phase measurements with sensitivity beyond the shot noise limit(SNL).

In this letter, we report tunable squeezing of 0.9dB resulting from injection locking of laser diodes. A frequency range of ~1.7 GHz is obtained around the cesium D_2 line by tuning the frequency of the master laser. This tunable nonclassical light can be used directly in high sensitivity spectroscopy and in this case the signal-to-noise ratio(SNR) will surpass the SNL.[13,14]

The experimental setup is illustrated in Fig. 1. The master laser is a single-longitudinal-mode GaAlAs distributed Bragg-reflector(DBR) laser diode (Model SDL-5712-H1 from Spectrum Diode Lab Inc). The linewidth is about 3 MHz and the side mode suppression is more than 25 dB. Its frequency can be continuously tuned several GHz around the B line (852.356 nm) of the cesium D_2. The diode is driven by a constant-current laser diode driver (Model 505 of Newport Corp.). Its temperature can be actively stabilized to within 0.2% degree with a thermoelectric temperature controller (Newport Corp. Model 325). A collimator with a numerical aperture(N. A.) of 0.3 (Model 4017 of ILX Lightwave Inc) is used to collimate the output beam and a 40 dB optical isolator is used to avoid optical feedback. The slave laser is a GaAlAs quantum-well index-guided laser diode (Model SDL-5411-G1 of SDL Inc). It can operate in single mode under certain conditions, such as constant-current and no optical feedback. The maximum output power obtained with a collimating lens assembly of N. A. 0.6 (Model 06-GLC-001 of Melles Griot Inc.) is 100 mW under a driving current of 122 mA. The slave laser is mounted on a heat sink and driven by another constant-current laser diode driver, the same as the master laser's, its temperature also controlled to within 0.2% degree by another thermoelectric temperature controller(Model IDT-5910B of ILX Lightwave Inc.). In order to decrease additional noise of the master and slave laser coupled in from the drivers, we connect an inductance of 300 μH in series with the cathode of each other, by which means the noise peaks over a certain frequency range significantly reduced. An isolator consisting of two cube polarization primes (P and PBS_3), a half-wave plate and a 45-degree Faraday rotator in front of the slave laser, are used to avoid the reflection disturbance from the balanced detection system and the scanning Fabry-Perot cavity, and also to match the polarization of the injection beam from the master laser to the slave laser . The modes and wavelengths of the both lasers are monitored by the scanning Fabry-Perot cavity and a wavelength meter, respectively.

The amplitude noise of the slave laser is measured by the balanced detection system consisting of a half-wave plate, a beam splitter, a pair of balanced detectors , a +/− rf power combiner and an rf spectrum analyzer (SA) (Hewlett-Packard HP-8590L). The quantum efficiency of two symmetrical sillicon PIN photodiodes(EG&G Model FND-100) used as receiver in the balanced detectors is about 81% near 852 nm. For each photodiode, its dc photocurrent part is filtered

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out while its ac part is amplified by an amplifier with a bandwidth of 50 MHz. The amplifier output is either added or subtracted by the +/− rf power combiner. When set on the "−" position, it gives a rf signal proportion to the SNL, while in the "+" position, it gives the full amplitude noise of the beam incidence on the beam splitter.[8,9] The saturated photocurrent of each detector is above 13 mA, in other words, the detectors are linear up to 13 mA of photocurrent. The SNL level is calibrated from measurements of the signal light emitted from an LED with the same detection system.

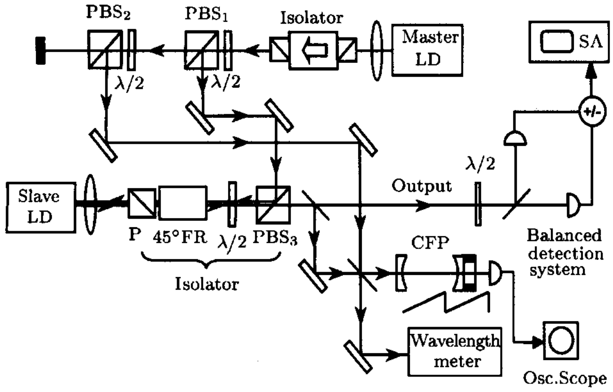

Fig. 1. Experimental arrangement for amplitude squeezing by injection locking of a laser diode; λ/2:half-wave plate, PBS: polarization beamsplitter , P: polarizer, CL: collimator; FR: Faraday rotator, CFP: confocal Fabry-Perot cavity, SA: RF spectrum analyzer.

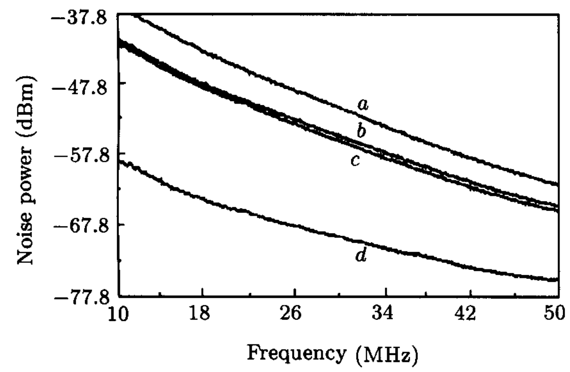

Fig. 2. Amplitude noise spectra of the injection-locked slave laser from 10 MHz to 50 MHz. (*a*) Without light injection; (*b*) shot-noise-limit(SNL). (*c*) With injection locking; (*d*) electronics noise. Parameters of RF spectrum analyzer: Resolution bandwidth:1 MHz; Video bandwidth:100 Hz.

The maser laser works at the wavelength (vacuum wavelength) of 852.356 nm, the B line of the cesium D_2 lines. When the slave laser is free running at a temperature of 20.51°C and driving current of 99.7 mA, which is well above the threshold current 12 mA($I/I_{\rm th}$ ≈ 8.3), its wavelength is 852.356 nm. The optical path of the maser laser needs to be adjusted carefully to make the injection beam strictly coincide with the output beam of the slave laser, with their polarization matched as well. With the maser laser's injection beam on, the slave laser can be injection locked. A triangular wave voltage from a function generator (Stanford Research Systems Model DS-335) with a frequency of 200 mHz is used to modulate the driving current of the master laser to sweep its frequency. The slave laser frequency follows the master laser continuously over a large frequency range. To a certain extent, the higher the injection power, the larger the frequency range that can be covered. While the master laser frequency is swept by modulating its driving current, the tunable frequency range of the slave laser is ∼1.7 GHz with an injection power of 1.5 mW at the entrance to the slave laser.

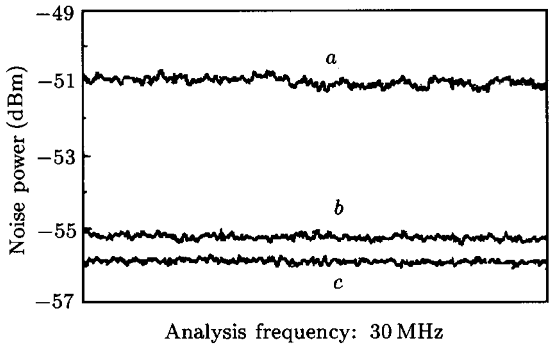

Fig. 3. Amplitude noise spectra at an analysis frequency of 30 MHz. (*a*) Without light injection; (*b*) shot noise limit(SNL); (*c*) with injection locking. Parameters of rf spectrum analyzer: Resolution bandwidth:1.0 MHz, video bandwidth:100 kHz.

In fact, there are many side modes around the main mode in a so-called single-mode laser diode, though their intensities are very low, more than 25 dB below the main mode's intensity. At high pump levels ($I/I_{\rm th} \ll 1$), side-mode intensities of the slave laser are slightly suppressed due to gain saturation and they almost all oscillate near the threshold, but the main mode operates well above the threshold. When these side modes are greatly suppressed, the mode partition noise further decreases,[9] which leads to the generation of amplitude squeezing. In an injection-locked laser diode the main mode is enhanced while the side modes are further suppressed, which can lead to amplitude squeezing.

We observe the amplitude noise with an HP-85901L RF spectrum analyzer over a frequency range of 10 MHz to 50 MHz (Fig. 2). The electronics noise(curve *d*) is about 16 dB below the SNL (curve *b*). Without the injection beam, the amplitude noise of the slave laser (curve *a*) is ∼4 dB above the SNL. After injection, the amplitude noise (curve *c*) is ∼0.8 dB below the SNL. This amplitude squeezing of ∼0.8 dB of the slave laser is directly measured throughout the tunable range. After taking into account the overall efficiency, the amplitude squeezing at the output facet of the slave laser should be 0.9 dB. Figure 3 shows the spectrum of amplitude noise at an analysis frequency of 30 MHz.

Nevertheless, when the modes between the master laser and the slave laser are not optimally matched or the injection power is not strong enough, the amplitude noise of the slave laser will increase. This is probably caused by the onset of the coherence collapse or the increase of power in the side modes.[22] In the mean time, sweeping the frequency of the master laser by modulating its driving current will induce additional amplitude noise due to residual amplitude modulation(AM).[23] But in our case the residual AM is very weak since the slave laser is operated at a pump level of 8.3 times the threshold, i.e. highly saturated, therefore AM is strongly suppressed.[13]

In conclusion, tunable amplitude squeezed light of 0.9 dB has been observed in a laser diode with light injection. While the master laser frequency is tuned, amplitude squeezing of the slave laser can be maintained throughout a tunable range of $\sim$1.7 GHz around the cesium D_2 line. This tunable nonclassical light source offers us a possibility to study the interaction between cesium atoms (thermal or cold atoms) and non-classical light, so that we can observe the interaction below the shot noise limit.

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