Reducing the phase noise in diode lasers

R.L. RINCON C.[1] AND M. MARTINELLI[1]

[1] Institute of Physics, University of São Paulo. Rua do Matão Tr. R 187, CEP: 05508-090, São Paulo-SP, Brazil.
[*] Corresponding author: rlrinconc@usp.br

Compiled May 31, 2019

Diode lasers are widely used in atomic physics given its narrow linewidth and wavelength tunability. Nevertheless, although they present a low noise for their intensity, their excessive noise in the phase limits their application in quantum optics. Looking for the reduction of this phase noise, we built and characterize a ring laser, using a semiconductor tapered amplifier as the gain medium. We were able to reduce the phase noise of a diode laser to a factor of 10 above shot noise level, bringing it closer to a useful coherent state for applications in quantum information.

http://dx.doi.org/10.1364/ao.XX.XXXXXX

1. INTRODUCTION

The low cost of diode lasers and their versatility made them ubiquitous in science and technology. Beyond their applications in telecommunications, they became particularly successful as a source of tunable light for atomic physics, and are widely used on applications involving metrology or atomic clocks, trapping and cooling techniques [1]. They can provide narrow linewidth fields [2], whose characteristics are comparable to much more sophisticated designs involving optically pumped lasers, like those using dyes or crystals as the gain medium. Many linewidth narrowing techniques have been implemented, using additional elements to extend the cavity of the laser beyond the chip. Some popular designs for these External Cavity Diode Lasers are the Littrow [3] and Littman-Metcalf [4] configurations, that include diffraction gratings as a cavity element for extended tunability.

Intensity and phase noise on these lasers present some distinct characteristics. Working in free running configuration, they may present small intensity noise, reaching to the point of direct generation of intensity squeezing, i. e., quantum fluctuations below the limit given by a coherent state [5], but with an excess of phase noise as high as 80 dB [6]. Much effort was devoted to the reduction of intensity noise, achieving squeezing in this quadrature with values around 3 dB at 10K or 2 dB at room temperature using the injection-locking [6, 7]. For the external cavity laser, people have found intensity squeezing around 1.6 dB [6]. Such compression comes with the drawback of excess noise in phase fluctuations. Excess of phase noise of 46 dB can be found in the injection locking scheme and 70 dB for the external cavity, way above the uncertainty limit. This high noise level restricts the application of diode lasers in the generation of coherent light, since the filtering of this noise would demand filtering cavities whose bandwidth would be below the one of the laser source, draining much of its power.

We present a method for controlling the noise level on diode lasers, reducing the total noise power to levels close to 10 dB above the coherent state noise level. While it is yet above the typical result for a Ti:sapphire laser, it is an improvement of 2 orders of magnitude compared to usual cavity configurations used for applications in atomic physics.

Much of the phase noise can be associated to the Schawlow-Townes linewidth [8]. In the laser cavity, spontaneous emission will add random fluctuations to the resonant field resulting from the balanced process of gain in the laser medium and cavity loss. While the feedback given by the saturation of the gain stabilizes the amplitude of the field, the absence of feedback for the phase leads it to a diffusive process that reduces the coherence time of the field. The coherence time will be proportional to the power of the field, the square of the cavity lifetime, and will be reduced by the contribution of spontaneous emission to the laser mode. Taming these parameters is crucial for the control of phase noise [9, 10]. A simple model based on the evaluation of the Schawlow-Townes linewidth results in a estimation of the phase noise power (normalized to vacuum noise units) given by [11]

$$S_q(\omega) = 1 + 2\kappa^2(1+\alpha^2)/\omega^2, \tag{1}$$

being κ the cavity decay rate, $\omega = 2\pi\nu$ with ν the analysis frequency and α the enhancement factor [12], associated to the coupling of intensity and phase fluctuations in the amplifying medium, that is strongly dependent on the medium.

The contribution of phase diffusion to the noise in diode lasers is therefore enhanced by many different effects. The fact that the lasing medium is compact leads to designs where the extended cavities are small, of the order of 0.1 m. The high gain leads to projects of cavities with low quality factor. Therefore the cavity has usually a large bandwidth. Moreover, linear cavities will usually present standing waves leading to spatial hole burning [13]. The regions of the laser covering the nodes of the oscillating mode of the cavity will have reduced contribution to the amplification. However, these regions can also incoherently contribute to the intracavity field, leading to additional noise. Finally, in semiconductor lasers, the fluctuation in the population inversion is associated to an additional fluctuation of the refractive index of the medium, leading to a significant enhancement factor α for the Schawlow-Townes linewidth (known as Henry factor [12]). Nevertheless, the high gain of the amplifying medium allows for a tunable, single-mode output, with typical linewidths of the order of 100 kHz, and reasonable power (of the order of mW), being widely used in atomic physics.

When more stringent specifications of the light beam are involved, such as narrower linewidth, higher power and lower noise levels, Ti:sapphire or dye lasers are often used. The gain medium is free from the Henry factor enhancement, has an extremely broadband gain, but this gain is one order of magnitude smaller than the one of the diode laser. Closed cavity configurations are then preferred for continuous operation. To ensure single line operation, a ring cavity is used to inhibit the spatial hole burning and an intracavity optical diode selects the oscillating direction of the traveling wave. Finally, a sequence of spectral filters control the oscillating wavelength. With all those elements, the resulting cavity will be quite long (typical values of 1 m). These characteristics will lead to a narrower bandwidth of the cavity, resulting in a noise level that is limited to that of a coherent state, at a cost of a more complex and expensive cavity design for a stable and robust operation. Final results can lead to narrow linedwidths (< 100 kHz) and output power up to 1 W.

We show that by combination of some characteristics from the typical Ti:sapphire laser design with a tapered diode amplifier, a relevant reduction of the phase noise can be achieved, bringing laser diodes into reasonable conditions for quantum optics implementations. We make a direct comparison of the results to those obtained in a typical tunable laser diode in the Littrow configuration, showing the difference in the noise performance of both systems.

2. EXPERIMENTAL SETUP

Most of the commercial diodes used in atomic physics are built on a chip, with one face coated for total reflection and the other one just cleaved, forming an open cavity. This configuration if useful to build a linear cavity, but makes it inconvenient for a ring one. Therefore, to build a ring cavity using a diode laser as a gain medium, we have chosen a tapered amplifier $TL219$ extracted from a $SDL-8630$ laser, whose internal elements for making a Littman cavity where removed. It has a peak gain at 782 nm, and a maximum operational current of 1.57 A, delivering more than 0.5 W at this condition. The narrow side of the amplifier, that was facing the diffraction grating, has a reduced reflection, and the original output beam was provided from the broader side of the amplifier, facing a cylindrical lens for astigmatism correction.

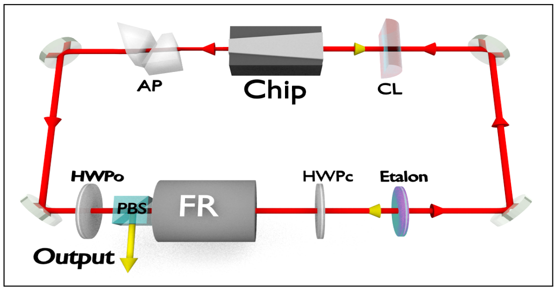

Fig. 1. Ring cavity around the diode laser chip. The yellow arrow represents the **CW** propagation that is blocked at the PBS and the red line is the **CCW** beam. AP stands for anamorphic prism and CL for cylindrical lens.

We used this tapered amplifier in the ring cavity design that is shown in Figure 1. The astigmatism of the light emitted from the narrow facet of the chip (propagating counter clockwise in the diagram, indicated by the red arrow) is corrected by a pair of anamorphic prisms (AP), while the correction of the astigmatism of light emitted from the wide facet, in the clockwise (CW) propagation (yellow arrow), is made by the original cylindrical lens (CL).

The light in the counter clockwise propagation (CCW) has a controllable loss by the adjustment of the orientation of the half wave plate HWP_o right before a polarizing beam splitter (PBS), an pass through a Faraday rotator (FR). The polarization is adjusted back to horizontal by a half waveplate (HWP_c). This beam is then injected at the front facet of the tapered amplifier. The CW propagation coming from this facet is reflected by the PBS, and therefore cannot perform a roundtrip in the cavity. The overall cavity length for the CCW mode is 2 m, and its output coupler is the reflection from the front facet of the amplifier. Further selection of the longitudinal mode is provided by the etalon, with thickness of 600 μm, whose resonance that can be adjusted by the tilting of the glass plate.

The diode has a self-oscillating threshold for 0.7 A of injected current, resulting from residual reflectance of the diode facets forming a cavity. Below this value, we have tested the transmittance of the amplifier by injection of a weak seed beam at the gain peak (782 nm) through the rear facet, and verified that the amplification threshold is close to 0.4 A, what would be consistent with a three level laser model [13].

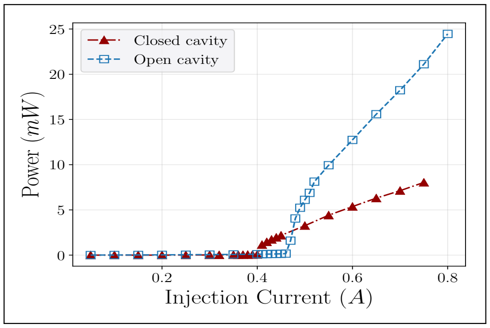

Fig. 2. Output power of the cavity in the two configurations, closed (red triangles) and open (open blue squares).

We show two main results for two different configurations of the cavity, playing with the losses by the orientation of the waveplate HWP_o. The output power for different injection currents is shown in Figure 2. For the closed configuration (minimal losses), the threshold value is 0.41 ± 0.01 A and the maximum output power for single mode operation is around 8 mW. Notice that the threshold value is pretty close to the amplification limit for the three-level model of the gain medium. Setting additional losses to 50% by reorienting the half-wave plate, the threshold increases to 0.47 ± 0.01 A. This polarization rotation will also increase the output coupling of the cavity, therefore higher power can be reached, until the limit of 12 mW before multimode operation. The multimode operation is clearly seen with the help of a confocal Fabry-Perot cavity. The field presents a series of modes with a separation that is compatible with the laser cavity free spectral range of 150 MHz. If the etalon is removed, the multimode operation is frequently observed even close to the threshold.

Further characterization was made by the measurement of the laser linewidth. On the closed cavity configuration, we measured the beat note with a stabilized Ti:Sapphire laser, with a linewidth of 70 kHz. From the convolution of the measured width the beatnote, we could observe a linewidth of 390 kHz for our laser, compatible with usual values of diode lasers [3, 4].

The resulting single mode laser has output power and linewidth compatible with regular diode lasers in linear cavity configuration. Therefore, we could make a direct comparison with of the produced noise with those of a laser in Littrow configuration, formed by a blazed diffraction grating of 1800 lines/mm and a diode laser *Sanyo DL7140-201S* centered at 780 nm.

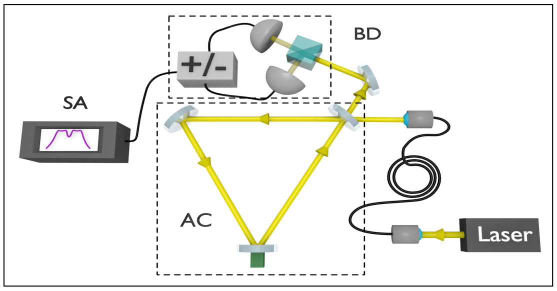

Fig. 3. Measurement setup for the noise measurement using the self-homodyning technique. The beam under study goes to an analysis cavity (AC) which is continuously detuned. The reflected beam from the cavity goes to a balance detection scheme (BD). Its output is recorded in an spectrum analyser (SA).

In order to measure the amplitude and phase noise of the single-mode beams, we used the self-homodyne detection scheme, consisting on a scanning cavity (AC) and a balanced detection (BD), as shown in Figure 3. The light reflected of a single port ring cavity is divided on a 50/50 beam splitter and measured by two detectors. By summing their intensities, we recover the intensity fluctuations of the light beam, while by their subtraction we recover the equivalent noise for a coherent state of the same average power (vacuum homodyning) [14]. The noise is measured by a spectrum analyser (SA) on zero-span mode for different analysis frequencies, with resolution bandwidth (RBW) of 1 MHz and video bandwidth (VBW) of 100 kHz. The cavity plays a role of converting phase to intensity noise when the field is close to one of its resonances [6, 15, 16]. The cavity bandwidth is the main limitation for evaluation of the noise for lower analysis frequency. In the present case, the bandwidth of the analysis cavity is 7 MHz. The beam was injected into the cavity through an optical fiber for two reasons. From one side, it enables the simple switch from one laser to another for the comparison of their noise power. Moreover, the single mode fiber filters the spatial mode of the laser, ensuring a mode matching of the output of the fiber into the cavity in excess of 98 %. Mismatch and losses on the system will reduce the power reaching the balanced detection by a factor of 3.

3. RESULTS

A typical result of the noise measurement is shown in Figure 4. For comparison, we present a typical result from our ring laser at a closed cavity configuration, with a current of 0.87 A and an output of 6.0 mW, and the usual result from a diode in the Littrow configuration, delivering the same power on the detectors. Far from the resonance, we obtain the amplitude noise of the laser. As we scan the cavity, phase noise is converted into amplitude noise, and for the Littrow configuration we can see the rising of the noise level reaching 32 dB at the half-width of the cavity ($\Delta = \pm 0.5$), where we have nearly complete conversion of the phase noise into amplitude. The precise evaluation of the noise for both quadratures is given by the adjust of the expressions for the amplitude noise spectrum given by eq. (25) in [16], as shown in the continuous line in the curves.

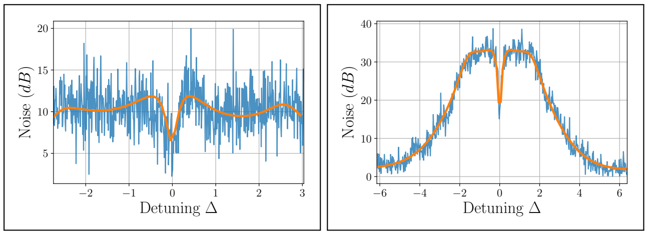

Fig. 4. Normalized intensity noise of the laser beams after reflection of a scanning cavity. Noise is normalized to the noise of a coherent state, and cavity detuning is normalized to the cavity bandwidth. Left: noise from the ring cavity laser, right: noise from a reference Littrow diode laser. Analysis frequency of 15 MHz, laser power of 2.7 mW on balanced detection.

As can be seen, the diode in the usual Littrow configuration presents intensity fluctuations near the shot noise limit (0 dB for the amplitude), but a huge excess noise in the phase, while the present ring cavity configuration shows only a small variation of the noise according to the measured quadrature of the field. Nevertheless, a honest comparison of lasers of different intensities requires a proper normalization.

Considering for instance two coherent states, with different mean photon number $\langle \hat{n}_i \rangle$, with i standing for the mode. Both fields will have the same variances for the fluctuations of the field, but different values for the intensity fluctuations, that will follow a Poissonian distribution $\Delta \hat{n}_i^2 = \langle \hat{n}_i \rangle$. An initial treatment of those fields used the *Mandel Q parameter* [17], which describes the normalized intensity noise as $Q = \frac{\Delta^2 \hat{n}}{\langle \hat{n} \rangle} - 1$. This measure is useful for comparing intensity fluctuations, given that $Q = 0$ for Poissonian statistics, and positive values for excess noise in the intensity. Nevertheless, the measured Q parameter of a field, under attenuation, will vary linearly, being therefore dependent under losses. A strong field may have a higher Q than a weaker one, but once it is attenuated to the value of the weaker field, it can present a better noise figure.

In order to compensate for this dependence, we considered a monomode quantum field whose bosonic field operator is given by $\hat{a} = a + \hat{p} + i\hat{q}$. Choosing a real valued a results in having $\hat{p}$ and $\hat{q}$ as the quadrature operators for the amplitude and phase fluctuations, respectively. Since the Q parameter changes linearly upon attenuation, we have compared the measured Q values normalized to the measured laser power, defining this normalized Q parameter as

$$Q_{Norm} = \frac{Q}{P_{laser}} = \frac{1}{P_{laser}} \left(\frac{\Delta^2 p}{\Delta^2 p_o} - 1 \right), \tag{2}$$

where, $\Delta^2 p$ is the fluctuation on the measured quadrature, $\Delta^2 p_o$ is the fluctuation of the quadrature of a coherent state with the same average power, and P_{laser} is the power in one detector. This modified definition allows us a direct comparison between sources of light with different power and noise level. A source with high noise level Q but also high power can show, under this renormalization, if its noise figure can beat that of a weaker beam upon direct attenuation.

Figure 5 shows the *Normalized Q parameter*, evaluated at 15 MHz for the closed (left) and open (right) configurations of the ring laser. The variation of measured power (at the balanced detection) corresponds to a variation in the injection current of the chip. It is clear that as the pump is increased beyond the threshold, the effective noise is reduced, what is consistent with the usual description of the noise in the laser. Moreover, while the noise in phase (q quadrature) is always bigger than the noise of the amplitude, they are always of the order of magnitude. Furthermore, it is clear that for the same power, the closed cavity beats the noise figure of the open cavity, which is consistent with the longer lifetime of the photon in the closed cavity (Eq. 1). Nevertheless, even for an open cavity the result is yet much better than that of a Littrow cavity laser.

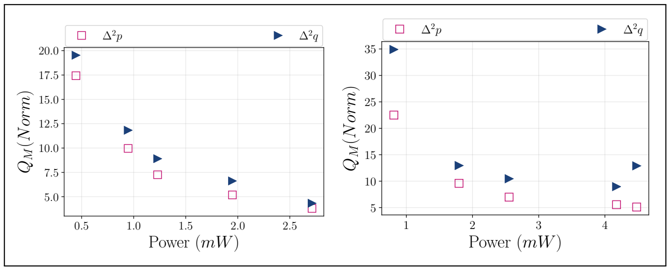

Fig. 5. Excess of noise represented by the Q parameter, as a function of the laser power for 15 MHz for the closed cavity (left) and an open configuration (right).

Table 1 emphasizes the results we obtained in this work, for operational conditions of Figure 4. It compares the noise level between our system (ring cavity) in the closed configuration, open configuration and the Littrow external cavity scheme. For the same output power, the Littrow configuration has a low intensity noise, close to the shot noise level, while the ring cavity presents a significantly higher noise, that could be associated to the conversion of phase to amplitude noise by narrowband elements as the etalon, and the narrower linewidth of the cavity itself. However, phase noise in Littrow configuration is two orders of magnitude higher, and the advantage of the ring configuration becomes evident.

Table 1. Noise comparison for the ring and Littrow laser.

Laser configuration	**Δ^2p(dB)**	**Δ^2q (dB)**
Ring cavity (closed)	10.5(0.1)	11.1(0.1)
Ring cavity (open)	13.8(0.1)	17.7(0.1)
Littrow cavity	1.6(0.2)	33.6(0.2)

We may have a good comparison if we consider the application of these lasers as a master source for problems in quantum optics requiring that the field has the noise reduced to that of a coherent state. A commonly used technique is to build an impedance matched cavity with a bandwidth of cavity capable of filtering the excess noise [18]. For the operation at 15 MHz, a Littrow laser would request a cavity with bandwidth of less than 300 kHz, of the order of the laser linewidth. On the other hand, for the ring cavity, a 4 MHz cavity would be enough for the filtering. Or, seen the other way, the same filtering cavity would give effective coherent output for a much broader range of frequencies for the ring laser than for the linear cavity configuration.

4. CONCLUSIONS

We have shown that the use of a ring configuration with a closed cavity can strongly reduce the excess noise in diode lasers. While this configuration provides a narrower cavity bandwidth, thus helping to compensate for the Henry factor in semiconductors, we believe that the elimination of stationary waves in the gain medium is also a relevant factor, reducing the contribution of spontaneous emission to the total noise that should be present in linear cavity configurations.

We believe that this laser source can be useful for advanced studies in atomic physics and quantum optics, where high power is not necessary. Moreover, further investigation can demonstrate if low noise operation for output power of the order of 100 mW can be achieved, therefore matching the stringent limits set by Ti:sapphire lasers at a much lower cost. Coarse tunability of the system could be achieved by temperature tuning of the maximum gain of the amplifier, and fine tuning can be performed by the mode selection of the etalon combined with fine adjustment of the diode current and of the cavity length.

Grant #2015/18834-0, São Paulo Research Foundation (FAPESP); Grant #133721/2016-7, National Council for Scientific and Technological Development (CNPq).

The authors would like to thank P. Nussenzveig for useful discussions.

REFERENCES

1. C. E. Wieman and L. Hollberg, Rev. Sci. Instruments **62**, 1 (1991).
2. T. P. Dinneen, C. D. Wallace, and P. L. Gould, Opt. Commun. **92**, 277 (1992).
3. R. Wyatt and W. J. Devlin, Electron. Lett. **19**, 110 (1983).
4. K. Liu and M. G. Littman, Opt. letters **6**, 117 (1981).
5. F. Marin, A. Bramati, E. Giacobino, T.-C. Zhang, J.-P. Poizat, J.-F. Roch, and P. Grangier, Phys. Rev. Lett. **75**, 4606 (1995).
6. T.-C. Zhang, J.-P. Poizat, P. Grelu, J.-F. Roch, P. Grangier, F. Marin, A. Bramati, V. Jost, M. Levenson, and E. Giacobino, Quantum Semiclassical Opt. J. Eur. Opt. Soc. Part B **7**, 601 (1995).
7. H. Wang, M. J. Freeman, and D. G. Steel, Phys. Rev. Lett. **71**, 3951 (1993).
8. A. L. Schawlow and C. H. Townes, Phys. Rev. **112**, 1940 (1958).
9. A. Grabmaier, G. Fuchs, A. Hangleiter, R. Glew, P. Greene, and J. Whiteaway, J. Appl. Phys. **70**, 2467 (1991).
10. H. G. Shiraz, *The Principles of Semiconductor Laser Diodes and Amplifiers* (Imperial College Press, London, 2004).
11. T. Zhang, J.-P. Poizat, P. Grelu, J.-F. Roch, P. Grangier, F. Marin, A. Bramati, V. Jost, M. Levenson, and E. Giacobino, Fourth Int. Conf. on Squeezed States Uncertain. Relations (1996).
12. C. Henry, IEEE J. Quantum Electron. **18**, 259 (1982).
13. A. E. Siegman, *Lasers* (Mill Valley, CA, 1986).
14. H. A. Bachor and T. C. Ralph, *A Guide to experiments in quantum optics* (Wiley-VCH Verlag GmbH & Co., 2004).
15. P. Galatola, L. Lugiato, M. Porreca, P. Tombesi, and G. Leuchs, Opt. Commun. **85**, 95 (1991).
16. A. S. Villar, Am. J. Phys. **76**, 922 (2008).
17. L. Mandel and E. Wolf, *Optical coherence and quantum optics* (Cambridge university press, 1995).
18. B. Willke, N. Uehara, E. Guftafson, R. Byer, P. Kings, S. Seel, and R. Savage Jr, Opt. Lett. **23** (1998).

FULL REFERENCES

1. C. E. Wieman and L. Hollberg, “Using diode lasers for atomic physics,” Rev. Sci. Instruments **62**, 1–20 (1991).
2. T. P. Dinneen, C. D. Wallace, and P. L. Gould, “Narrow linewidth, highly stable, tunable diode laser system,” Opt. Commun. **92**, 277–282 (1992).
3. R. Wyatt and W. J. Devlin, “10 khz linewidth 1.5 μm ingaasp external cavity laser with 55 nm tuning range,” Electron. Lett. **19**, 110–112 (1983).
4. K. Liu and M. G. Littman, “Novel geometry for single-mode scanning of tunable lasers,” Opt. letters **6**, 117–118 (1981).
5. F. Marin, A. Bramati, E. Giacobino, T.-C. Zhang, J.-P. Poizat, J.-F. Roch, and P. Grangier, “Squeezing and intermode correlations in laser diodes,” Phys. Rev. Lett. **75**, 4606 (1995).
6. T.-C. Zhang, J.-P. Poizat, P. Grelu, J.-F. Roch, P. Grangier, F. Marin, A. Bramati, V. Jost, M. Levenson, and E. Giacobino, “Quantum noise of free-running and externally-stabilized laser diodes,” Quantum Semiclassical Opt. J. Eur. Opt. Soc. Part B **7**, 601 (1995).
7. H. Wang, M. J. Freeman, and D. G. Steel, “Squeezed light from injection-locked quantum well lasers,” Phys. Rev. Lett. **71**, 3951 (1993).
8. A. L. Schawlow and C. H. Townes, “Infrared and optical masers,” Phys. Rev. **112**, 1940 (1958).
9. A. Grabmaier, G. Fuchs, A. Hangleiter, R. Glew, P. Greene, and J. Whiteaway, “Linewidth enhancement factor and carrier-induced differential index in ingaas separate confinement multi-quantum-well lasers,” J. Appl. Phys. **70**, 2467–2469 (1991).
10. H. G. Shiraz, *The Principles of Semiconductor Laser Diodes and Amplifiers* (Imperial College Press, London, 2004).
11. T. Zhang, J.-P. Poizat, P. Grelu, J.-F. Roch, P. Grangier, F. Marin, A. Bramati, V. Jost, M. Levenson, and E. Giacobino, “Phase noise reduction of laser diode,” Fourth Int. Conf. on Squeezed States Uncertain. Relations (1996).
12. C. Henry, “Theory of the linewidth of semiconductor lasers,” IEEE J. Quantum Electron. **18**, 259–264 (1982).
13. A. E. Siegman, *Lasers* (Mill Valley, CA, 1986).
14. H. A. Bachor and T. C. Ralph, *A Guide to experiments in quantum optics* (Wiley-VCH Verlag GmbH & Co., 2004).
15. P. Galatola, L. Lugiato, M. Porreca, P. Tombesi, and G. Leuchs, “System control by variation of the squeezing phase,” Opt. Commun. **85**, 95–103 (1991).
16. A. S. Villar, “The conversion of phase to amplitude fluctuations of a light beam by an optical cavity,” Am. J. Phys. **76**, 922–929 (2008).
17. L. Mandel and E. Wolf, *Optical coherence and quantum optics* (Cambridge university press, 1995).
18. B. Willke, N. Uehara, E. Guftafson, R. Byer, P. Kings, S. Seel, and R. Savage Jr, “Spatial and temporal filtering of a 10-w nd:yag laser with a fabry–perot ring-cavity premode cleaner,” Opt. Lett. **23** (1998).