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Interband Cascade Laser Photon Noise

by Patrick Folkes

ARL-TR-4981 September 2009

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Adelphi, MD 20783-1197

ARL-TR-4981 **September 2009**

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REPORT DOCUMENTATION PAGE	***Form Approved*** ***OMB No. 0704-0188***

1. REPORT DATE *(DD-MM-YYYY)* September 2009	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
4. TITLE AND SUBTITLE Interband Cascade Laser Photon Noise		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Patrick Folkes		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. .Army Research Laboratory ATTN: RDRL-SEE-I 2800 Powder Mill Road Adelphi, MD 20783-1197		**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-4981
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

We report measurements of the low-frequency photon noise and the relative intensity noise of an interband cascade laser as a function of laser current at 30 K and 100 K. Away from threshold, the laser primarily exhibits a frequency-independent photon noise spectral density in agreement with theory. At threshold, the observed photon noise spectral density exhibits large fluctuations at closely-spaced discrete frequencies. Thermal effects at 100 K result in a large increase in the photon noise above threshold.

15. SUBJECT TERMS

Semiconductor

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Patrick Folkes
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	22	**19b. TELEPHONE NUMBER** (*Include area code*) (301) 394-1042

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

It is a pleasure to acknowledge insightful discussions with R. Tober and J. Bradshaw. The lasers used in this study were grown by F. Towner and fabricated by C. Monroy.

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Summary

We report the first measurements of the low-frequency interband cascade (IC) laser photon noise and relative intensity noise (RIN) as a function of constant-wave (cw) laser current at 30 K and 100 K. Just below and above threshold, the IC laser primarily exhibits a frequency-independent photon noise spectral density in agreement with theory. At threshold, the observed photon noise spectral density exhibits large fluctuations at closely spaced discrete frequencies. At 30 K the dependence of the IC laser photon noise and the RIN on current qualitatively agrees with theory. Thermal effects at 100 K result in a much larger increase in the photon noise, with increasing current than theoretically predicted, and significant disagreement between the observed and theoretical dependence of the RIN on current. Further studies are needed to understand the observed thermal effects on IC laser photon noise, photon fluctuations at threshold, and the excess low-frequency photon noise. The reported IC laser photon noise measurements are useful in the design and analysis of system performance in various applications of the IC laser.

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1. Introduction

The interband cascade (IC) laser (*1, 2*) is a relatively new type of semiconductor mid-infrared (IR) light source that is based on radiative transitions between the conduction and valence bands in type-II semiconductor quantum wells (QWs). Type-II unipolar IC lasers use the type-II band alignment in Sb-based QW structures and an applied potential to obtain a staircase-like band structure, allowing each injected electron to cascade down a series of injection and active regions resulting in a quantum efficiency which is greater than one, which is the limit in interband diode lasers (*1–3*). Quantum cascade (QC) lasers (*4,5*) use a similar recycling of injected electrons to achieve lasing from stimulated intersubband transitions in a series of coupled QWs. Since the early experimental studies of the IC laser (*6-11*) improved material quality, device design and fabrication have led to significant improvements in IC laser performance (*12–17*). Mid-IR lasers are needed for commercial and military applications such as chemical sensing, IR countermeasures, free space communications, and IR ladar. The spectral density of fluctuations in the output power of the IC laser—referred to as photon noise or laser intensity noise—is an important device performance parameter for these potential applications. However, no theoretical or experimental investigation of the IC laser photon noise has been reported. In this report we report constant-wave (cw) measurements of the IC laser photon noise and relative intensity noise as a function of current at 30 K and 100 K.

Comprehensive theoretical models (*18, 19*) of the photon noise in QC lasers have been developed. The theoretical model for the QC laser photon noise, which is based on a three-level coupled QW active region, is quite general; its main features are qualitatively applicable to the IC laser. The QC laser noise theory is based on linearization of the coupled set of nonlinear rate equations to obtain rate equations for the fluctuations in electron and photon density. All gain sections in the IC laser are connected in series. As a result, the electron density fluctuations in different gain stages are all coupled to the photon density fluctuations and the fluctuations in the current through the active regions. Current fluctuations are suppressed by electronic correlations and the small differential resistance of each gain stage compared with the total laser differential resistance. The theory assumes that, away from threshold, fluctuations can be modeled by small Langevin noise sources, which results in a frequency-independent (white noise) photon noise spectral density for frequencies that are small compared to the laser modulation frequency. The theory is not applicable at threshold because the use of completely random Langevin noise sources and the linearization of the rate equations are not valid procedures at laser threshold (*20*). Above threshold, the contribution of non-radiative recombination processes to the QC laser photon noise is dominant and increases with bias current (*18, 19*). This is in contrast to interband diode lasers, where spontaneous emission is the dominant noise source above threshold (*21, 22*).

2. Experiment

The IC laser structure has 18 active regions that are separated by an injection region composed of digitally graded Indium Arsenide (InAs)/Aluminum Indium Antimonide (Al(In)Sb) multi-QWs. The active region consists of coupled InAs, Gallium Indium Antimonide(GaInSb) and Gallium Antimonide (GaSb) QWs separated by Aluminum Antimonide (AlSb) barriers. Under bias, electrons that are injected into the InAs QW, undergo radiative or non-radiative interband transitions into the GaInSb QW, tunnel into the adjacent GaSb QW, and then enter the next injection region by interband tunneling. The laser structures were grown by molecular-beam-epitaxy and processed into mesa-stripe lasers with a mesa-width of 15 µm and a 1 mm cavity length. Both facets of the laser cavity were left uncoated. The lasers were mounted on a chip carrier, which was affixed to the cold finger of a low-temperature cryostat for measurement. Measurements were not carried out at temperatures higher than 100 K to avoid degradation of the IC laser. The 3.45 µm emission from one facet of our IC laser was focused onto a 1 mm diameter Judson Indium Antimonide (InSb) photodetector, whose output is fed into an amplifier with a constant gain over the frequency range 0–203 KHz. Based on previous measurements of the laser's far-field pattern and our collection optics, we estimate that 70% of the total output power from the facet is collected. The laser output power is proportional to the direct current (dc) output of the amplifier. The low-frequency spectral density of the laser photon noise was measured by a Hewlett-Packard spectrum analyzer, taking into account the thermal noise from the amplifier and the photodetector. Measurements of the photodetector current over the range of laser output power show that the photodetector current shot noise is negligible compared to the observed photon noise associated with fluctuations in the output power of the IC laser.

3. Results

The measured photon noise spectral densities over the frequency range 5 KHz–100 KHz of a typical laser at 100 K and 30 K are shown in figures 1 and 2, respectively, for various cw laser currents. The spectrum analyzer's local oscillator signal appears over the range 0–5 KHz range. The laser threshold current, I_{th}, is approximately 9.7 mA and 3.1 mA at 100 K and 30 K, respectively. For laser currents slightly above threshold, the observed photon noise spectral density, S_f, is predominantly constant for frequencies greater than around 16 KHz, indicating that above threshold, the laser photon noise primarily has a white noise spectrum in agreement with theory (*18, 19*). At 30 K we observe a sharp decrease in the white noise component of S_f as the current, I, is increased above threshold to 4.4 mA. The 30 K white noise is insensitive to I over the range 4.4 mA < I < 10.2 mA, and then increases by roughly a factor of 10 as I is increased from 10.2 mA to 30.2 mA. Theory (*18*) predicts the sharp decrease in S_f above threshold followed by a factor of 3.5 increase in S_f, with increasing current over the range $2 < I/I_{th} < 10$. In contrast, the measured 100 K white noise component of S_f increases by a factor of around 600 when the laser current is increased from 10.2 mA to 27.3 mA. The observed large increase in the 100 K S_f with increasing current indicates that thermal effects result in a significant increase in the IC laser photon noise due to increased non-radiative recombination.

The photon noise spectral density has a low-frequency excess noise component that can be approximately fitted by a $1/f^2$ dependence over the 5 KHz–16 KHz range, as shown in figure 1, by the $1/f^2$ fit to the 10.2 mA excess photon noise over the range 3 KHz $\leq f \leq$ 16 KHz. The 30 K data shows that the excess noise component increases monotonically with current. At 100 K the ratio of the low-frequency excess noise at 5 KHz to the white noise increases from 25 dB to 26 dB, as the laser current is increased from 10.2 mA to 15.4 mA and then decreases to 22 dB as the current is increased to 27.3 mA. Figure 3 shows that the 100 K photon noise spectral density changes to a $1/f^{1.6}$ frequency dependence over the range 5 KHz–80 KHz when the current is increased from 27.3 mA to 37.9 mA. The mechanism for this change in the photon noise spectrum is unknown, but the change is clearly induced by thermal effects. The observed temperature and current dependence of the low-frequency excess noise confirms that it is associated with photon fluctuations and not with low-frequency photodetector current fluctuations. The mechanism for the low-frequency excess photon noise could be similar to the deep-level trap mechanism responsible for generation-recombination noise (*23*) and mode-competition noise (*24*) in interband diode lasers.

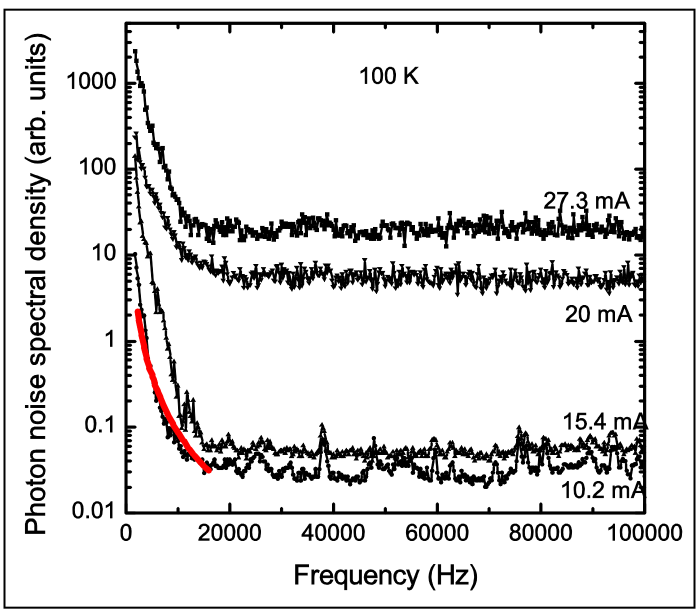

Figure 1. Photon noise spectral density at 100 K for several cw laser currents. The thick solid line in the 10.2 mA plot is a $1/f^2$ fit to the data.

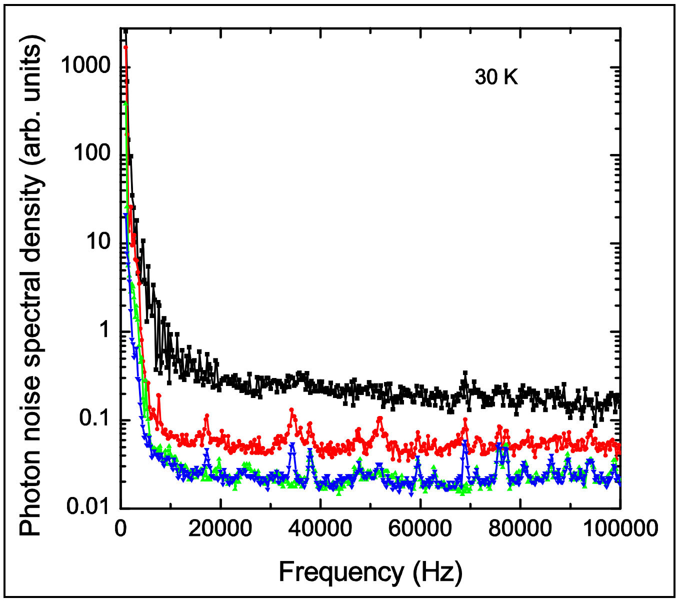

Figure 2. Photon noise spectral density at 30 K for laser currents of 4.4 mA, 10.2 mA, 21.4 mA, and 30.2 mA. Note that the 4.4 mA and the 10.2 mA plots nearly overlap.

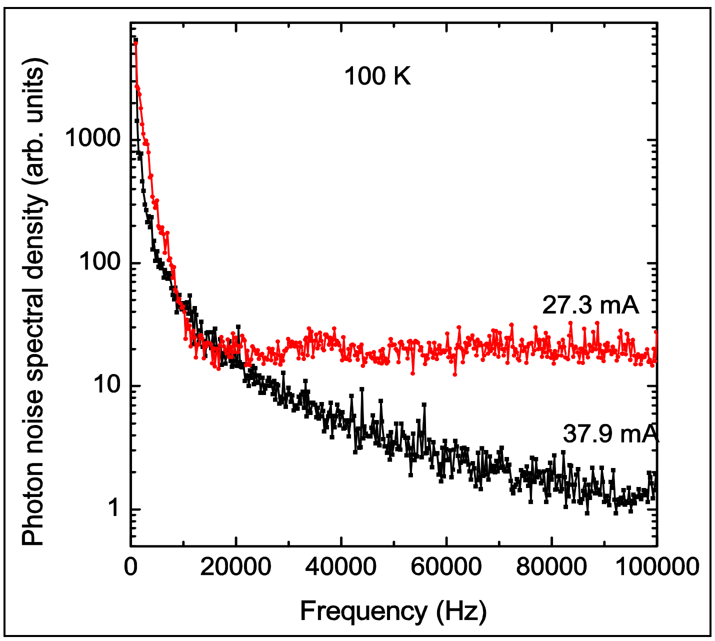

Figure 3. Photon noise spectral density at 100 K for laser currents of 27.3 mA and 37.9 mA.

The laser RIN is an important figure of merit, given by the expression RIN (db/Hz) = 10log (S_f / P^2), where S_f is the photon white noise spectral density and P is the laser output power. The average S_f over the range 20 KHz–100 KHz is used to determine the RIN. The measured RIN at 30 K and 100 K is shown in figure 4 as a function of I/I_{th}. The measured RIN data takes into account the collection efficiency and the fact that light is collected from only one facet. At 30 K the measured RIN monotonically decreases from a value of –105 dB at threshold to around –162 dB for $I/I_{th} > 5$, in good qualitative agreement with the theoretical results (*18*) shown in figure 4. Over the range $1 \leq I/I_{th} \leq 3$, the measured 30 K RIN approximately shows a $1/P^2$ dependence in agreement with theoretical and experimental results (*19*, *25*). Figure 4 shows that at 100 K, the measured RIN decreases from –112 dB at threshold to –152 dB at $I/I_{th} = 1.6$, and then increases to –134 dB at $I/I_{th} = 2.9$. The observed increase in the RIN, with increasing current over the range $1.6 < I/I_{th} < 3$ at 100 K, disagrees with theoretical prediction. The mechanism for the observed increase in the IC laser 100 K RIN is not known, but the data clearly indicates that the increased cavity temperature induces an increase in photon fluctuations. For $1 < I/I_{th} < 2$, the observed IC laser RIN at 30 K and 100 K is about 15 dB smaller than the QC laser RIN (*25*). For $I/I_{th} > 4$, the 30 K IC laser RIN is comparable to the 88 K QC laser RIN, while the 100 K IC laser RIN is about 15 dB higher than the 88 K QC laser RIN.

At 30 K, figure 5 shows that the laser exhibits a white noise spectrum just below threshold at I = 3.0 mA. At threshold, I = 3.14 mA, we observe striking large fluctuations at closely spaced discrete frequencies in the photon noise spectral density. We observe the same striking changes in the 100 K photon noise spectral density as the current is increased from below threshold at I = 9.5 mA to $I = I_{th} = 9.73$ mA, shown in figure 6. Figures 1 and 2 show that the large fluctuations in the photon noise spectral density are not observed above threshold. The 30 K photon noise spectral density at threshold closely resembles that observed at 100 K. The frequencies at which the large photon fluctuation peaks are observed at 30 K are nearly identical to those observed at 100 K, which suggests the possibility that the large low-frequency photon fluctuations observed at threshold may be correlated.

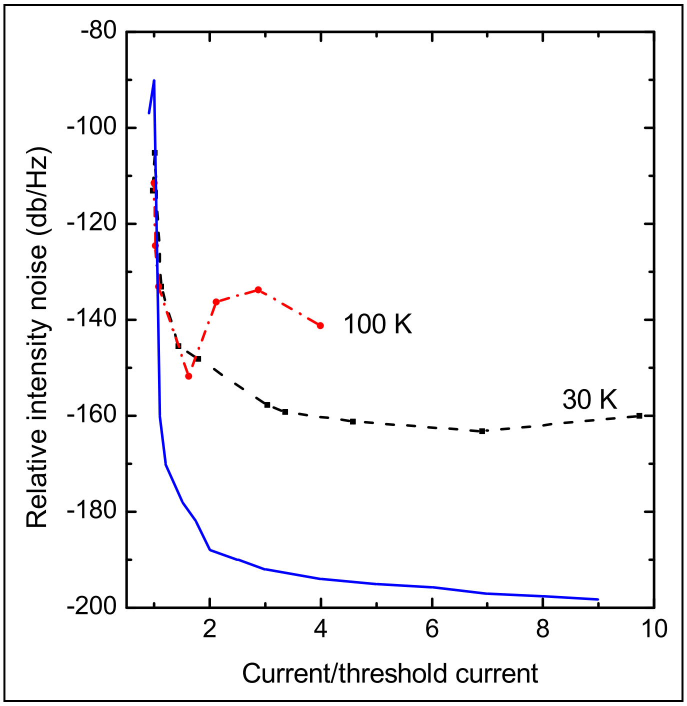

Figure 4. RIN as a function of laser current at 30 K and 100 K. The solid line shows theoretical RIN from reference 18.

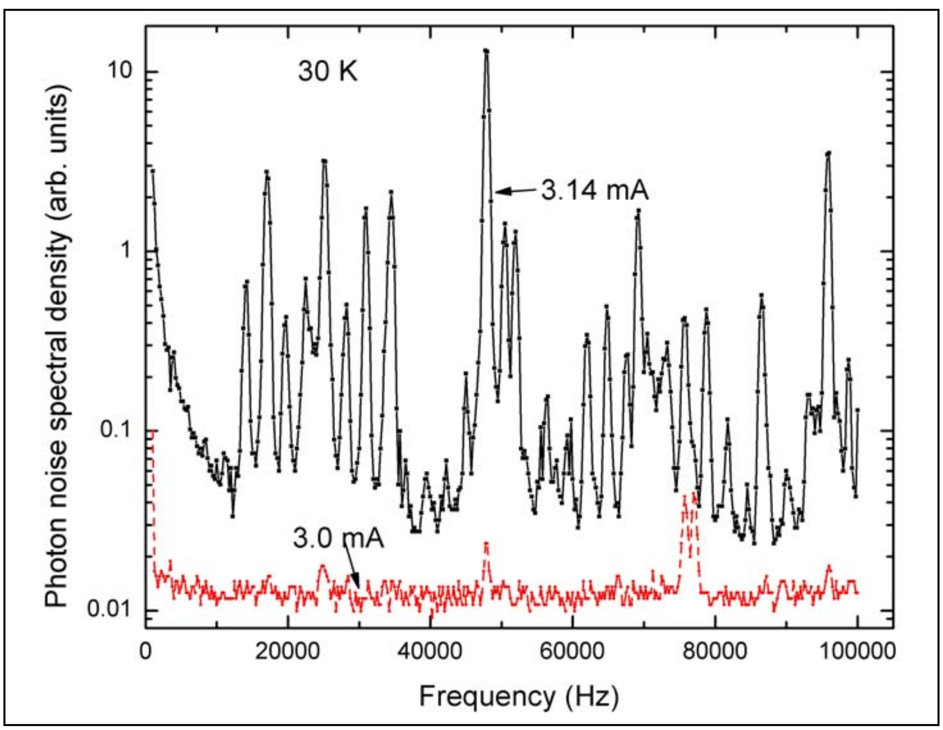

Figure 5. Photon noise spectral density at 30 K just below threshold (3.0 mA) and at threshold (3.14 mA).

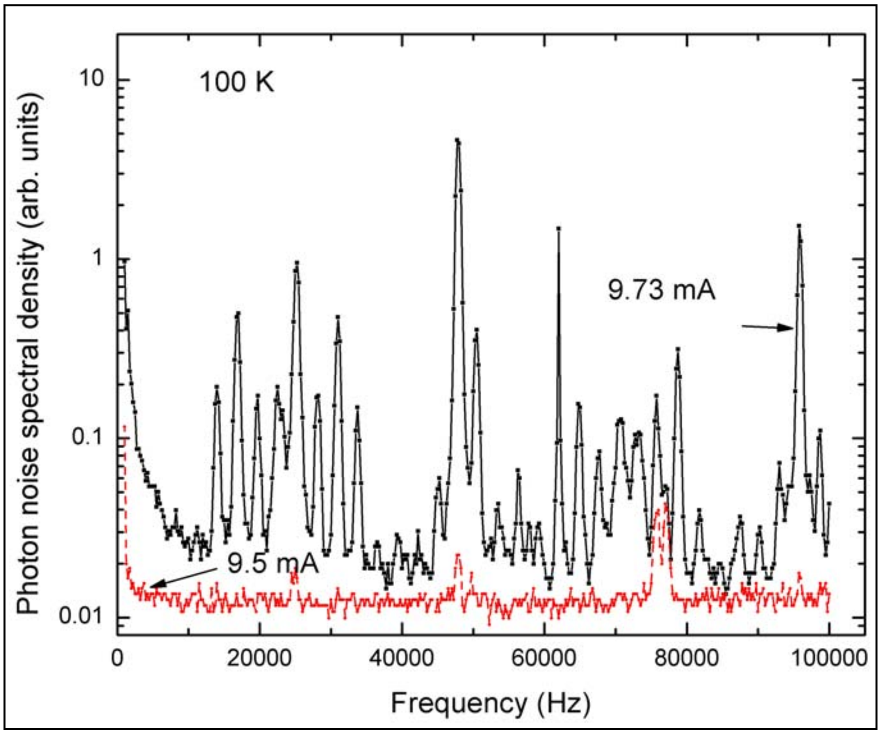

Figure 6. Photon noise spectral density at 100 K just below threshold (9.5 mA) and at threshold (9.73 mA).

4. Conclusion

In conclusion, we report the first cw measurements of the low-frequency IC laser photon noise and relative intensity noise as a function of laser current at 30 K and 100 K. Just below and above threshold, the IC laser primarily exhibits a frequency-independent photon noise spectral density in agreement with theory. At threshold, the observed photon noise spectral density exhibits large fluctuations at closely-spaced discrete frequencies. At 30 K, the dependence of the IC laser photon noise and the RIN on current qualitatively agrees with theory. Thermal effects at 100 K result in a much larger increase in the photon noise, with increasing current than theoretically predicted and significant disagreement between the observed and theoretical dependence of the RIN on current. Further studies are needed to understand the observed thermal effects on IC laser photon noise, photon fluctuations at threshold, and the excess low-frequency photon noise.

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List of Symbols, Abbreviations, and Acronyms

AlSb	Aluminum Antimonide
AlInSb	Aluminum Indium Antimonide
cw	constant wave
DC	direct current
GaSb	Gallium Antimonide
IC	Interband cascade
InAs	Indium Arsenide
InSb	Indium Antimonide
IR	Infrared
QC	Quantum cascade
QW	Quantum well
RIN	Relative intensity noise

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