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Nonlinear Dynamics of Interband Cascade Laser Subject to Optical Feedback

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Abstract: We present a comprehensive study of the nonlinear dynamics of long external cavity de-10 layed optical feedback induced interband cascade lasers(ICL). Using the modified Lang-Kobayashi 11 equations, we numerically investigate the effects of some key parameters on the first Hopf bifurca-12 tion point of ICL with optical feedback, such as delay time(τ_f), pump current(I), linewidth enhance-13 ment factor(LEF), stage number(*m*) and feedback strength. It is found that compared with τ_{f} , *I*, LEF 14 and *m* have significant effect on the stability of the ICL. Additionally, our results show that for few 15 stage number ICL subject to external cavity optical feedback is more susceptible to exhibiting 16 chaos. The chaos bandwidth dependence on m, I and feedback strength are investigated, and 12 17 GHz bandwidth mid-infrared chaos is observed. 18

Keywords: interband cascade laser; mid-infrared chaos; optical feedback; nonlinear dynamics

1. Introduction

The interband cascade laser(ICL) as a mid-infrared semiconductor laser has made 22 significant progress in the last two decades[1-6]. The RAND Corporation reports that mid-23 infrared lasers in the 3-5 μm band of the atmospheric transmission window have good 24 atmospheric transmission characteristics, lower transmission losses than other bands, and 25 is less susceptible to weather factors[7]. In addition, the mid-infrared band covers the 26 absorption peaks of many atoms and molecules[8]. Therefore, it can be used in applica-27 tions such as gas detection[9,10], clinical respiratory diagnosis[11] and free-space optical 28 communication[12]. 29

In contrast to Quantum cascade lasers (QCLs), the ICL is a bipolar device with the 30 electronic transition of the ICL occuring between the conduction band and the valence 31 band[13]. Therefore, the carrier lifetime of ICL is of nanosecond order as in more con-32 ventional semiconductor lasers. Also in recent experimental reports the linewidth en-33 hancement factor of ICLs is found to be about 2.2 which is much higher than that of 34 QCLs[14]. Both of these characteristics suggest that when subject to external perturba-35 tion the ICL will exhibit rich nonlinear dynamics. Wang Cheng et al.'s recent experiments 36 confirm that with external optical feedback ICL present periodic oscillations and weak 37 chaos[15]. 450 MHz low frequency oscillation (detector bandwidth limited) chaos was 38 observed. However, the route to chaos and the identification of means for obtaining 39 strong chaos are open for detailed study. 40

In this paper, modified Lang-Kobayashi equations are used to investigate the dynamics of ICL subject to external optical feedback. Considering the spatial length of the light path in many experiments, we focus on the long-cavity optical feedback case, 43 wherein the external feedback time lag is larger than the oscillation relaxation time of 44

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the f ICL[16]. The pump current, feedback strength, stage number and linewidth enhance-45 ment factor effects on stability of ICL are analyzed, and the influence of *m*, *I* and feedback 46 strength on the bandwidth of chaos. 47

2. Theoretical model

Figure 1a presents the ICL structure with stage number of 3. Initially the electron 49 transition in the ICL occurs between the first conduction band and the first valence band 50 as indicated as E_e (blue potential well) and E_h (red potential well) in the left upper corner 51 Figure 1a[17]. After the first time electron transition, the electron reaches the second stage 52 conduction band through interband tunneling, and then repeats the electron transition 53 in the second stage and then in the third stage. Figure 1b is the schematic diagram of an 54 ICL subject to external mirror feedback, where τ_f is the feedback time delay. 55



Figure 1. (a) 3 stage number structure of ICL; (b) Schematic diagram of ICL with optical feedback structure.

Appropriately modified Lang-Kobayashi equations, by adding an optical feedback 59 term in optical fields, rate equations of ICL with mirror optical feedback are as fol-60 lows[18,19] 61

$$\frac{dN(t)}{dt} = \eta \frac{I}{q} - \Gamma_p \upsilon_g g S - \frac{N}{\tau_{sp}} - \frac{N}{\tau_{aug}}$$
(1)

$$\frac{dS(t)}{dt} = \left[m\Gamma_g \upsilon_g g - \frac{1}{\tau_p}\right] S(t) + m\beta \frac{N}{\tau_{sp}} + 2k\sqrt{S(t)S(t - \tau_f)}\cos\theta(t)$$
(2)

$$\frac{d\varphi(t)}{dt} = \frac{\alpha_{\rm H}}{2} \left[m\Gamma_p v_g g - \frac{1}{\tau_p} \right] - k \sqrt{\frac{S(t - \tau_f)}{S(t)}} \sin\theta(t)$$
(3)

where N(t), S(t) and $\varphi(t)$ respectively represent carrier number, photon number and phase 63 of the electric field. *m* is number of the cascade gain stage, τ_{sp} is the spontaneous radia-64 tion lifetime and τ_{aug} is the Auger recombination lifetime. Since the Auger recombination 65 lifetime τ_{aug} in ICL is smaller than the spontaneous radiation lifetime τ_{sp} , τ_{aug} must be 66 considered in the current-carrying dynamics [20]. η is the current injection efficiency, Γp is 67 the optical confinement factor per gain stage, v_g is the group velocity of light, g is the ma-68 terial gain per stage. τ_p is photon lifetieme, and k is the feedback efficient which is given 69 by $k = 2C_l \sqrt{f_{ext}}/\tau_{in}$, where τ_{in} is the internal cavity roundtrip time, f_{ext} is the feedback 70 strength which is defined as the power ration between the feedback light and the laser 71 output, and C_l is an external coupling coefficient. The external coupling coefficient can be 72 expressed as $C_l = (1 - R)/2\sqrt{R}$, with R is the reflection coefficient of the laser front facet facing the external mirror. 74

The steady-state solutions for the ICL operating above the threshold current are as follows[19]

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$$S = m\eta\tau_p \frac{I - I_{th}}{q}$$
(5)

$$I_{th} = \frac{q}{\eta} \left(\frac{1}{m} \frac{A}{\Gamma_p v_g a_0 \tau_p} + N_{tr} \right) \left(\frac{1}{\tau_{sp}} + \frac{1}{\tau_{aug}} \right)$$
(6)

The descriptions of other symbols and the selected values for simulation are shown 79 in Table 1, as taken from [14,17,19-22]. The integral time lag in the simulation is 0.1ps. 80

Table 1. ICL parameters used in the simulations.

Parameter	Symbol	Value
Cavity length	L	2mm
Cavity width	W	4.4µm
Group velocity of light	${\cal V}_{\cal G}$	8.38×10 ⁷ m/s
Wavelength	λ	3.7µm
Active area	А	8.6×10 ⁻⁹ m ²
Facet reflectivity	R	0.32
Refractive index	Nr	3.58
Optical confinement factor	Γ_p	0.14
Stage number	m	5,10
Injection efficiency	η	0.64
Photon lifetime	$ au_p$	10.5ps
Spontaneous emission time	$ au_{sp}$	15ns
Auger lifetime	auaug	1.08ns
Threshold current	$I_{ m th}$	16.6mA (<i>m</i> =5)
Feedback strength	fext	0~60%
Time delay	Tf	1~3ns
Differential dain	$lpha_0$	2.8×10 ⁻¹⁰ cm
Transparent carrier number	N_{tr}	6.2×10 ⁷
Spontaneous emission factor	β	1×10^{-4}
Linewidth enhancement factor	lphaH	2.2

3. Numerical results

We calculate the carrier numbers and photon numbers as bias current increases as84shown in Figure 2a and 2b, respectively. It is found that stage number m has little effect85on carrier numbers(in Figure 2a) but it influences photon numbers(in Figure 2b). For rel-86ative largestage numbers such as m=10, the output power is much higher than the case87m=5(black) as shown in Figure 2b.88

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Figure 1. Carrier number (a) and photon number (b) vs. pump current. Black solid and red dashed 90 curves present stage number *m*=5 and *m*=10 respectively. 91

3.1. Route to chaos

Figure 3 shows the output of the ICL with external optical feedback as the feedback 93 strength increases, for the case m = 5. The ICL output is stable when the feedback strength 94 f_{ext} ranges from 0 (i) to 0.07%. Without feedback, that is $f_{ext}=0$, the relaxation oscillation 95 frequency fr can be observed from RF spectrum (d-i) to be 1.79 GHz. This is in accord-96 ance with the value 1.794 GHz obtained by calculating the relaxation oscillation fre-97 quency via the relation $f = 1/[2\pi (G_0 S/\tau_p)^{-1/2}]$, where $G_0 = \Gamma_p v_g a_0 / A$. As the feedback strength 98 increases the ICL enters into period-1 dynamics (ii), quasi-periodic dynamics (iii), mul-99 tiple-period oscillations (iv), then displays chaos (v). The frequency of period-1 oscilla-100 tions is 1.85GHz as shown in Figure 3(d-ii), which is little larger than the relaxation oscil-101 lation frequency of the ICL. As the feedback strength increases, quasi-periodic oscillation 102 is found, which is confirmed by RF spectrum and phase diagram, that is more frequencies 103 are induced in Figure 3(d-iii) and more loops are found in the phase in Figure 3(c-iii), 104 respectively. Also multiple-period dynamics is observed as shown in Figure 3(a-iv) to 105 Figure 3(e-iv). For further Feedback strength increase more complex nonlinear dynamics 106 is introduced hence achieving mid-infrared optical chaos, as shown in Figure 3(a- v) to 107 3(e-v). In the optical spectra of the chaos shown in Figure 3(e-v), many external cavity 108 modes are found. This can be confirmed from the auto-correlation functions shown in 109 Figure 3(b-v), where the sidelobe peak is at 2.4 ns corresponding to cavity length 36 cm. 110

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Figure 3. Output of ICL with external optical feedback as feedback strength increases with m=5, $I=1.1I_{th}$, and $\tau_f=2.4$ ns; from the top down, I: $f_{ext}=0.0\%$, ii: $f_{ext}=0.1\%$, iii: $f_{ext}=0.1\%$, iv: $f_{ext}=0.3\%$, v: $f_{ext}=3\%$; columns (a)-(e) are time series(TS), autocorrelation 113 curves(ACF), phase portrait(P), radio-frequency spectrum(RF) and optical spectra(OS), respectively. 114

By using bifurcation diagrams, the dynamics of ICL as feedback strength increasing 116 can be obtained as shown in (a-i) with m=5 and (b-i) with m=10. Maximum Lyapunov 117 exponents can be used to determine whether the ICL output with external optical feed-118 back is chaos (red) or not (blue) as shown in Figure 4(a-ii) and 4(b-ii). As shown in Figure 119 4(b-i), the route to chaos for a 10-stage ICL with external optical feedback is from stable 120 state to period-1, then quasi-period and then chaos. This route is different from that of a 121 5-stage ICL where multiple-period oscillations are not observed. This shows that stage 122 number *m* impacts the route to chaos of an ICL subject to optical feedback. 123



Figure 4. Bifurcations(i) and Max Lyapunov exponents(ii) of ICL with external optical feedback un-126 der *I*=1.1*I*th, *τ*_{*f*}=2.4 ns. (a): *m*=5, (b): *m*=10. 127

3.2. Hopf bifurcation analysis

In this section, we explore the stability of ICLs with external optical feedback. We 129 first compare two stage numbers which are m=5 and m=10 to reveal the effects of time 130 delay, bias current and linewidth enhancement factor on the Hopf bifurcation points. Then ascertain how the Hopf bifurcation changes for stage numbers *m* in the range 1 to 20.

The pump current is set a little above threshold current, that is $1.1I_{\text{th}}$. Figure 5. Shows 134 that the external cavity delay has little effects on Hopf bifurcation point values . As the 135 external cavity delay increases from 1.0 ns to 3.0 ns, the Hopf bifurcation point values, 136 that is feedback power ratio for ICL enters into period-1, are in around 0.05% to 0.7%. 137 There is a jump value for τ_f =1.2 ns, in which case f_{ext} =1.2%. 138



Figure 5. Hopf bifurcation points vs. time delay τ_f for $I=1.1I_{th}$

To illustrate pump current effects, the Hopf bifurcation points versus bias currents 141 are investigated. In Figure 6a and 6b, two external cavity delays are compared, viz τ_f =1.2 142 ns and τ_f =2.4 ns. As the pump current increases the Hopf bifurcation point gradually 143 increases, in both *m*=5 (squares) and *m*=10 (circles) cases, as well as τ_f =1.2 ns and τ_f =2.4 144 ns. Compared with τ_f =2.4 ns, τ_f =1.2 ns needs larger feedback power ratio to enable the 145

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ICL to enter into unstable state, which is around 1.4 times of that of τ_f =2.4 ns at pump 146 current is 3*I*th. Since these two delays for Hopf bifurcation point values versus bias currents have similar trends, we focus our attention on τ_f =2.4 ns in the following results. 148



Figure 6. Hopf bifurcation points vs. bias currents. (a): $\tau_f = 1.2$ ns, (b): $\tau_f = 2.4$ ns.

It is well appreciated that the linewidth enhancement factor, α_{H} , plays a crucial role 151 in semiconductor laser nonlinear dynamics. For common quantum well laser diodes, $\alpha_{\rm H}$ 152 is in the range of 2.0 to 5.0. Recent report shows that the below-threshold linewidth en-153 hancement factor of ICL is in the range of 1.1-1.4. Here we calculate Hopf bifurcation 154 points versus linewidth enhancement factor which ranges from 1 to 5, as shown in Figure 155 7. As the linewidth enhancement factor increases from 1 to 2, the Hopf bifurcation point 156 value reduces rapidly, and then it tends to be stable as $\alpha_{\rm H}$ increases further. Thus small 157 $\alpha_{\rm H}$ imparts the ICL with considerable dynamic stability. 158



Figure 7. Hopf bifurcation points vs. linewidth enhancement factor under *I*=1.1*I*th, τ_f =2.4 ns. 160

For ICLs the cascade stage number *m* usually less than 20. Figure 8 shows Hopf bifurcation point values versus stage numbers with $I=1.5I_{th}$, $\tau_f=2.4$ ns. It is seen that as the stage number increases, Hopf bifurcation point values exponentially increases. 163

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Figure 8. Hopf bifurcation points values vs. stage numbers *m* with *I*=1.5*I*_{th}, τ *f*=2.4 ns.

3.1. Bandwidth of Chaos

A broadband RF spectrum is one of the significant characteristics of chaos. By using 167 80% power energy bandwidth measurement, we investigate the bandwidth of chaos. Similarly to regular quantum well laser diodes, the bandwidth of chaos from ICL with external optical feedback increases as the feedback power ratio increases , as shown in Figure 170 9.



Figure 9. Bandwidth of chaos vs. feedback power ratio under $I=1.1I_{\text{th}}$, $\tau_f=2.4$ ns, m=5 (black squares) and m=10 (red circles). 174

Increasing the pump current is expected to enhance the bandwidth of chaos and is 175 confirmed here in Figure 10. Here, we notice that mid-infrared chaos from ICL has same 176 regularity. Once the pump current increases to $2.2I_{\rm th}$, a 10 GHz chaos bandwidth is obtined when the stage number is 10, as shown in Figure 10. That is because occupying 178 main energy frequency component is relaxation frequency oscillation $f_{\rm R}$ increasing as 179 pump current.



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Figure 10. Bandwidth of chaos vs. bias current when feedback power ratio is 60% and τ_f =2.4 ns 182 with *m*=5 (black squares), *m*=10(red circles). 183

Figure 11 respectively present time series, auto-correlation, phase diagram, RF spec-184 trum and optical spectral of mid-infrared chaos for *m*=5 (in Figure 11a) and *m*=10 (in Fig-185 ure 11b). This indicates that for relative high stage number the bandwidth of chaos from 186 ICL is further enhanced as shown in Figure 11(a-iv) and (b-iv).

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Figure 11. Output chaos of ICL with external optical feedback as stage number increases with $I=1.9I_{th}$, $\tau_f=2.4$ ns and *fext*=60%. (a): *m*=5, (b): *m*=10.

The stage number effect is presented in Figure 12, where *m* ranges from 1 to 20 and 192 pump currents are $1.1I_{\rm th}$ (black squares) and $2I_{\rm th}$ (red circles). Although the increase in 193 bandwidth for relative high pump current, $2I_{th}$, is faster than that of the relatively low 194 pump current, $1.1I_{\text{th}}$, the tendency of the stage number effects is the same, that is the band-195 width of chaos increases as the stage number increases. This tendency is verified in Figure 196 9 to Figure 11. 197



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Figure 12. Bandwidth of chaos vs. stage number $I=1.1I_{th}$ (black squares) and $I=2I_{th}$ (red circles) with 199 $\tau_f = 2.4 \text{ ns.}$ 200

By using Max Lyapunov exponents, we distinguish chaos from quasi-period or pe-201 riod-1, and calculate the 80% energy power bandwidth versus feedback power ratio and 202 pump current as shown in Fig. 13. By using dashed curves, we distinguish period-1, quasi-203 period and chaos and find that as the stage number increases from 5 to 10, the quasi-period 204 region is extended as shown in Fig. 13 (a) and Fig. 13(b). For large stage number, that is 205

m=10, period-1 is observed when the pump current is above $2.2I_{th}$, as indicated in the left 206 upper corner of Fig. 13(b). The boundary of period-1 oscillations in Fig. 13(b) was al-207 ready presented in Fig. 6(b). Boundary of chaos between quasi-period and chaos reveals 208 that for relative few stage number an ICL with external optical feedback enters into 209 chaos easily as shown in Fig. 3(a). Both of these two stage numbers results confirm that 210 to obtain broadband mid-infrared chaos, one needs relative high pump current as well as 211 large feedback power ratio. Urthermore a 12 GHz bandwidth of mid-infrared chaos can 212 be obtained for *m*=10 as shown in the right up corner of Fig. 13(b). 213



Figure 13. Bandwidth vs. feedback power ratio and pump current, with τ_f =2.4 ns. (a): *m*=5, (b): *m*=10.

4. Discussion

Authors should discuss the results and how they can be interpreted from the per-220 spective of previous studies and of the working hypotheses. The findings and their impli-221 cations should be discussed in the broadest context possible. Future research directions may also be highlighted.

5. Conclusions

This section is not mandatory but can be added to the manuscript if the discussion is 227 unusually long or complex. 228

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