Improved feedback stability of semiconductor nanolasers by inclusion of a Fano mirror

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Summary: The photonic crystal Fano laser is presented, including the laser structure and theoretical model. The model is utilised to investigate numerically the sensitivity of the laser to external feedback with respect to the stability of the output signal, and the results are compared to the well-known behaviour of conventional Fabry-Perot-type lasers. The conventional operational regimes are observed, including continuous-wave, periodic modulation, pulse generation and chaos. However, it is then demonstrated how the narrowband reflectivity of the Fano mirror works to filter de-stabilising frequency components, leading to significantly better operational stability, so that the sensitivity toward external feedback is drastically improved.

1. Introduction

Photonic crystal (PhC) lasers are promising light sources for applications in photonic integrated circuits such as on-chip signal processing [1], with much progress being made towards thresholdless lasing [2] and integration onto silicon [3]. Recently, a novel type of PhC laser was realised by replacing one of the conventional laser mirrors by a Fano resonance, which creates a narrow resonance in the reflection spectrum [4]. This Fano laser (FL) showed desirable properties such as pinned single-mode lasing and self-pulsing [5], and it has been predicted that the laser has a modulation bandwidth greatly exceeding that of conventional lasers [6].

One particular issue for on-chip applications of semiconductor nanolasers is the lack of a readily available optical isolator, since it is well established that semiconductor lasers in particular suffer from high sensitivity to external feedback [7]. Even extremely weak external feedback on the order of -30 dB can lead to dynamic instabilities and chaos, undermining the operational reliability [8]. In this work, we compare the feedback stability of the Fano laser using an iterative travelling-wave model to the results for a conventional Fabry-Perot (FP) laser, as modelled using the well-known Lang-Kobayashi (LK) model for lasers with external feedback, and find that the Fano laser is significantly more resilient towards feedback-induced instabilities.

2. Fano laser structure and model

The Fano laser is realised in an InP photonic crystal membrane structure, as a line-defect waveguide with a nearby point defect H0 nanocavity, as shown in figure 1**(a)**. One laser mirror is created by termination of the waveguide, while the other mirror is formed by Fano interference due to the coupling of the continuum of waveguide modes to the discrete mode of the nanocavity.

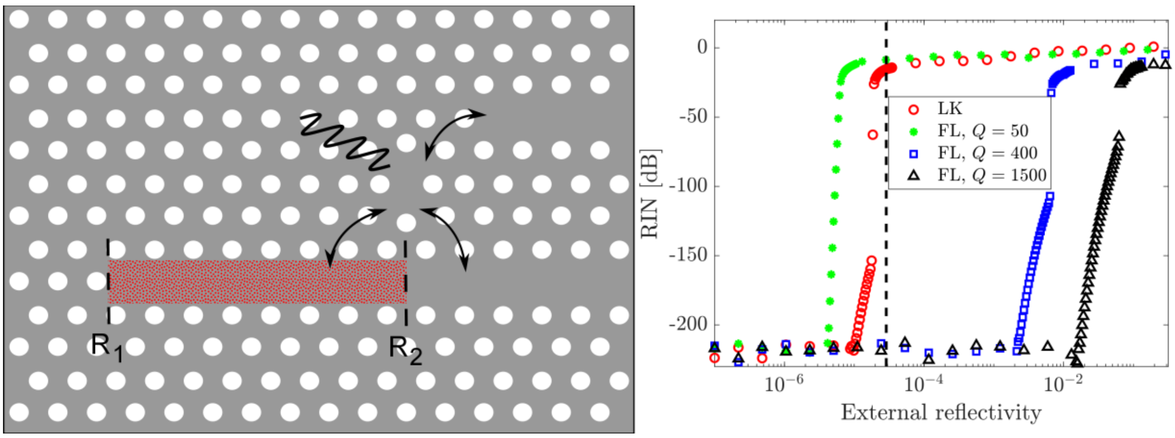

Figure 1: **(a)** Fano laser structure. The grey region is an InP membrane, and the white circles represent air holes. The laser mirrors are indicated, as are the coupling channels into and out of the nanocavity. The red dots represent the quantum dot active material. **(b)** Calculated relative intensity noise as function of the external power reflectivity for both the conventional laser (red circles) and the Fano laser (green, blue, black). As the quality factor of the Fano laser increases, so does the feedback stability, due to the narrowing of the mirror linewidth, far outperforming the conventional laser. The dashed black line indicates an analytical prediction for the onset of coherence collapse for the Lang-Kobayashi model.

This coupling leads to a narrow resonance in the reflection spectrum with a bandwidth inversely proportional to the Q-factor of the nanocavity. The active material of the laser consists of InGaAs quantum dots embedded in the membrane, and the device is pumped optically.

The dynamics of the Fano laser are modelled using an iterative travelling wave model, where the evolution of the laser cavity field is coupled to the nanocavity field, as described by coupled-mode theory, in order to account for the dynamic interference phenomenon that forms the laser mirror [4].

3. Feedback dynamics and stability comparisons

Figure 1**(b)** shows the calculated relative intensity noise (RIN) of the laser as a function of the external amplitude reflectivity for both the FP laser and Fano lasers with different Q-factors of the nanocavity. All other parameters are identical, including mirror reflectivity, laser threshold, and pump power. The RIN is calculated as

$$\mathrm{RIN} = \frac{\delta P^2}{\langle P \rangle^2} \tag{1}$$

where δP is the standard deviation of the output power and $\langle P \rangle^2$ is the square of the mean power. In the low Q-limit the FL curve approaches the LK curve. This agrees well with theory, where the FL model converges to the LK model if the feedback is weak and the nanocavity field can be adiabatically eliminated. As such, the green curve is essentially a convergence check, while the blue and black curves represent realistic FLs. We note here that spontaneous emission noise is excluded from the analysis, so that the RIN calculated by equation (1) is purely deterministic and is used to quantify the stability of the laser.

As the quality factor of the nanocavity is increased, the bandwidth of the mirror resonance decreases and the evolution of the FL RIN curve changes significantly. In particular, it is evident that the dramatic increase in RIN that signifies the onset of instabilities and chaos requires a significantly larger external reflectivity when the quality factor of the nanocavity is increased to realistic values. This significant increase in stability is attributed to the Fano mirror functioning as a narrowband filter, which decreases in linewidth as the quality factor is increased. As such, additional frequency components do not stay in the laser cavity to be amplified, retaining the narrow linewidth and stable operation even for large levels of feedback.

Generally, the shape and evolution of the RIN curves depend strongly on a number of parameters, including the pumping strength, delay time, and linewidth enhancement factor, but in all cases the Fano laser has a much lower feedback sensitivity than conventional FP lasers. For some parameter combinations, the difference in external feedback level for the conventional and Fano lasers at the onset of instability is orders of magnitude, showing how the nanocavity dynamics serve to strongly damp any fluctuations. This effect can also be observed by looking directly at the small-signal IM response, as in [6], where it was demonstrated how the IM response of the FL is damped in proportion to the quality factor of the nanocavity. This agrees with results for conventional lasers, where increased damping improves stability [7].

4. Conclusions

The Fano laser was presented, and it was demonstrated how the replacement of a conventional Fabry-Perot mirror by a Fano resonance in a photonic crystal laser may lead to improved feedback stability due to the strong dispersion of the Fano mirror. This was illustrated by calculations of the evolution of the relative intensity noise as the external feedback increases, showing how the onset of instabilities and chaos occur at a much higher external feedback for Fano lasers. The improved stability was attributed to the narrow bandwidth of the Fano mirror, which scales with the quality factor of the nanocavity, as was also observed for the feedback sensitivity.

5. References

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