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Quantum Optical Images in the Spatial Coherence Characteristics of Mesoscopic Semiconductor Lasers

1 Quantum optical images

While spatially inhomogeneous stimulated coherent emission may very successfully be described within a semiclassical framework, by its very nature, the corresponding processes leading to spontaneous emission are a signature of the nonclassical, quantum properties of the light-matter interaction in semiconductor structures. It is this nonclassical property of radiation which has recently received large interest. Particularly since the pioneering investigations of L. Lugiato *et al.* in systems of optical parametric oscillators (OPO), *quantum optical images* have revealed the nonclassical correlations between entangled photons created by down-conversion in the OPO [1]. Recently, it has been predicted that it should be possible in the OPO to generate pairs of optical images that are quantum entangled to each other[2]. While the OPO system allows a simplified level of description, the photonics of small semiconductor structures are considerably more complex. Most importantly, the light-matter interactions are strongly determined by the presence and the particular properties of the charge carrier system forming the microscopic (interband-) dipoles – the source of the radiation. Very uniquely, the dipole system thus carries both, the nonclassical properties of the carriers and the optical field [3].

In this contribution we will use a recently developed general theoretical model taking into account the spatiotemporal coherence of spontaneous emission. This is done on the basis of Quantum Maxwell-Bloch Equations [4] (QMBE) which describe the spatiotemporal dynamics of both, stimulated amplification and (amplified) spontaneous emission on equal footing in terms of expectation values of field-field correlations, dipole-field correlations, carrier densities, fields and dipoles. In particular, the quantum dynamics of the interaction between the light field and the carrier system is formulated in terms of Wigner distributions for the carriers and of spatially continuous amplitudes for the light field.

2 Spatial coherence characteristics of mesoscopic photonic semiconductor devices

2.1 Spontaneous emission in photonic semiconductor devices

In an optical semiconductor device, spontaneously emitted light may have significant influence on the spatiotemporal dynamics of the (coherent) light field. It is, in particular, a whole class of modern ultra bright resonant-cavity light emitting semiconductor diodes (RC-LED) which transform electric current with extreme efficiency (internal quantum efficiencies approaching 100%) into spontaneously emitted light. The spatial coherence of spontaneous emission and amplified spontaneous emission is equally most important in semiconductor lasers close to threshold, ultra low threshold semiconductor lasers [5] or spatially distributed or coupled semiconductor lasers systems like arrays of vertical-cavity surface-emitting lasers [6] (VCSEL) or multi-stripe and broad area semiconductor lasers. There, the spontaneous emission factor is modified by the amplification and absorption of spontaneous emission into the non-lasing modes and amplified spontaneous emission may be responsible for multi mode laser operation and for finite spatial coherence [6].

2.2 *Optical quantum images in the far-field of a RC-LED*

Resonant cavity LEDs (RC-LED) are a particularly important example of a mesoscopic photonic semiconductor device in which spontaneous emission is the source of radiation. There the spatial coherence of amplified spontaneous emission defines an angular distribution of the emitted light in the far field. From the Quantum Maxwell-Bloch equations an analytic expression for this distribution may be derived [4] which contains both gain/absorption due to stimulated emission and spontaneous emission:

$$I_f(\Theta,\Theta) = Wk_0 \frac{\arctan\left(\frac{\Omega_f-\omega(\Theta)}{\Gamma+\kappa}\right)+\arctan\left(\frac{\omega(\Theta)}{\Gamma+\kappa}\right)}{\pi(R+\frac{1}{2})-2\arctan\left(\frac{\Omega_f-\omega(\Theta)}{\Gamma+\kappa}\right)-\arctan\left(\frac{\omega(\Theta)}{\Gamma+\kappa}\right)},$$

$$\text{with} \quad R=\frac{2\hbar\kappa}{g_0^2\nu_0\sigma}\frac{m_{eff}^e+m_{eff}^h}{m_{eff}^e m_{eff}^h} \quad \text{and} \quad \omega(\Theta)=\frac{\omega_0\Theta^2}{2\epsilon_r}.$$

The parameter R represents the ratio between the cavity loss rate κ and the maximum amplification rate of the gain medium. g_0 is the normalized dipole matrix element, $m_{eff}^{e,h}$ the effective masses of electrons and holes, and Γ and Ω_f are the dephasing rate and Fermi frequency, respectively.

The classical laser threshold is defined by the carrier density for which the denominator of $I_f(\Theta,\Theta)$ is zero for a single specific frequency $\omega(\Theta)$. Consequently, the carrier density at which this occurs is pinned. Figure 1 shows the far field intensity distribution for different carrier densities below this pinning density.

In Fig. 1 (a), intensity distribution is for carrier densities much lower than the pinning density largely due to amplified spontaneous emission. The intensity maximum is clearly centered around $\Theta = 0$. Figure 1(b) shows the intensity distribution for carrier densities halfway towards threshold. Already, the intensity maxima move to angles of $\pm 15°$, corresponding to the frequency at which the gain spectrum has its maximum. In the case of Fig. 1(c), the threshold region is very close to the pinning density. The peaks in the far field pattern narrow as the laser intensity is increased.

3 Conclusions

Traces of *Quantum Optical Patterns* have been observed in spatially extended photonic semiconductor devices. An analytic expression derived from the Quantum Maxwell Bloch Equations shows images in the far-field which are a result of the spatial coherence of spontaneous

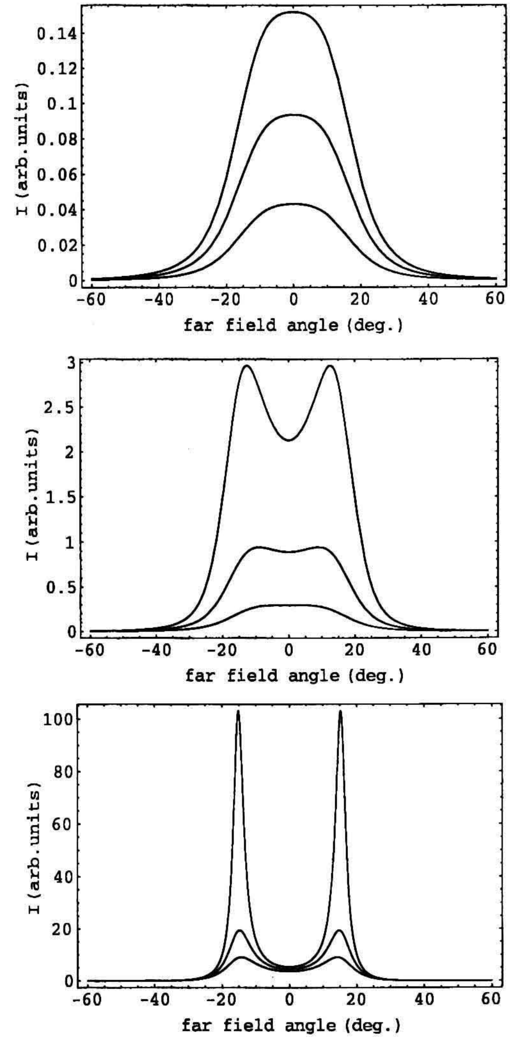

Figure 1: Fingerprints of the spatial coherence characteristics of quantum fluctuations in the formation of *Quantum Optical Image*: The cuts in the circularly symmetric far field intensity distribution of a broad-area RC-LED structure show the increased degree of spatial coherence with increasing carrier density.

and stimulated emission in a broad-area resonant-cavity light emitting diode (RC-LED). In the RC-LED the source of radiation is almost exclusively spontaneously emitted light and the far-field structures vanish if quantum-optical correlations are disregarded. Consequently, the far field pattern may indeed be regarded as a fingerprint of the quantum-optical spatial coherence – similar as the linewidth of the laser spectrum is a measure of temporal coherence.

References

[1] L.A. Lugiato, M. Brambilla, A. Gatti. In B. Bederson, H. Walter, editors, *Advances in Atomic, Molecular and Optical Physics*, volume 40. Academic Press, Boston (1998).

[2] L.A. Lugiato, M. Brambilla, A. Gatti, M.I. Kolobov. Phys. Rev. Lett. 83(1999) 1763–1766

[3] M. Kira, F. Jahnke, S. W. Koch. Phys. Rev. Lett. 82(1999) 3544–3547

[4] H.F. Hofmann, O. Hess. Phys. Rev. A 59(1999) 2342–2358

[5] Y. Yamamoto, R.E. Slusher. Physics Today (1993) 66–73

[6] H.F. Hofmann, O. Hess. Opt. Lett. 23(1998) 391–393

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