Spatio-temporal dynamics in Rayleigh band of photonic quantum ring laser

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Abstract - **Spatiotemporal dynamic simulations are used to analyze the carrier-field interactions of photonic quantum ring lasers in a three dimensional Rayleigh-Fabry-Perot toroidal cavity. After a few picosecond chaotic presence we observe tangled quantum wires-like re-distributions of recombinant carriers naturally formed in the Rayleigh band region of the active quantum well planes, exhibiting a transient photonic (de Broglie) quantum corral effect (PQCE) of a half-wavelength period.**

Chaotic electron movements in the 2-dimensional electron gas (2DEG) system can be found at places like the heterojunctions or atomic defect sites by the quantum interference between counter propagating electronic waves [1, 2]. Topinka et al. showed that an electron flow from the quantum point contact, fabricated in the 2DEG inside a GaAs/AlGaAs heterostructure, forms branching strands instead of spatially uniform spreading fans [3]. As for the formation of quantum wires, typical oscillation scales are reported to be about several nanometers [1-3], equivalent to half the Fermi wavelength of electrons. Despite the diversity of these experiments, they all involve systems in which the chaotic regimes are totally attributed to potential variations associated with structural discontinuities and randomly distributed impurities like defects and dopants.

In this paper, we investigate a quantum wire-like carrier ordering of naturally formed concentric photonic quantum rings (PQRs) in the multi-quantum well (MQW) planes induced by strong carrier-field interactions in a 3D whispering cave (WC) microcavity. Mesa type microcavities consist of vertical distributed Bragg reflector (DBR) structures added below and above the active MQW plane, and thus give rise to helical standing waves of 3D WC mode resonance toroid along the peripheral Rayleigh band for the PQR laser. (Figs. 1) [4, 5]. This PQR formation is responsible for the very low quantum-wire-like threshold currents and $\sqrt{T}$ -dependent thermal red shift. It is attributed to the PQCE which turns randomly populated carriers confined in MQW planes into λ/2 period concentric transient rings (λ=emission wavelength).

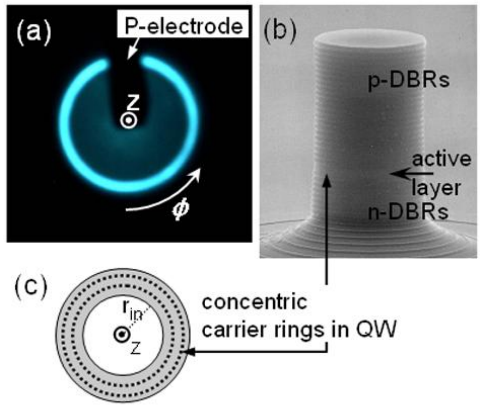

Fig. 1. (a) A CCD image of illuminant PQR laser (ϕ=15 μm) at I=30 μA; (b) cylindrical PQR structure; (c) concentric carrier rings within a $W_{Rayleigh}$.

We take a rectangular stripe area of Rayleigh bandwidth ($W_{Rayleigh)}$ for detailed numerical modeling, in the middle of a quantum well piece. This modeling converts cylindrical Bessel functions into sinusoidal functions, where the difference due to the coordinate transform turns out negligible for the typical toroidal microcavity of $W_{Rayleigh} < 1$ μm.

We now use a spatio-temporal dynamic model (STDM) for the PQCE analysis where we extend the traditional STDM to analyse both the electric field and dynamic carrier distribution in detail. The STDM is normally based on the Maxwell wave equation for the electric field and the Maxwell-Boltzman equation for carrier distribution [6, 7]:

$$\frac{\partial F}{\partial t} + \frac{\partial F}{\partial z} = iD_P \frac{\partial^2 F}{\partial x^2} + \Gamma(x)[g(N) - i\alpha a N]F \qquad (1)$$

$$\frac{\partial B}{\partial t} - \frac{\partial B}{\partial z} = iD_P \frac{\partial^2 B}{\partial x^2} + \Gamma(x)[g(N) - i\alpha a N]B \qquad (2)$$

$$\frac{\partial N}{\partial t} = D_f \frac{\partial^2 N}{\partial x^2} + J(x) - \gamma N - \Gamma(x) g(N)(|F|^2 + |B|^2) \qquad (3)$$

where, F and B are the forward and backward propagating (±z) optical fields, D_p is the diffraction coefficient, D_f is the transverse carrier diffusion constant, and more details are given in Ref. 7.

Figure 2 represents dynamic carrier and field distributions captured in transverse direction (x=0 plane) as a function of time up to 10 picoseconds. As the time advances carrier and field become strongly coupled, and initial carriers in uniform distribution start to be entangled in wavy patterns similar to the standing waves, while carrier and field distributions remain chaotic for initial period of a few psec. From the arrows of movement, we know the carrier velocity is 1.68×10^7 (=0.47 μm/2.8 psec, Fig. 2(b)) and 1.76×10^7 cm/sec (=0.3 μm/1.7 psec, Fig. 2(d)). We can further deduce the number of quantum wires and compare it with the PQR number χ within the W_{Rayleigh}. For example, in Fig. 2(b), we had W_{Rayleigh}=0.94 μm, equivalent to and χ~5.5 within the Rayleigh band (r in Fig. 1(b)), which gives a period of about 171 nm, and it is slightly larger than 130 nm (=850 nm/(2×3.28)) from the 'λ/2' assumption.

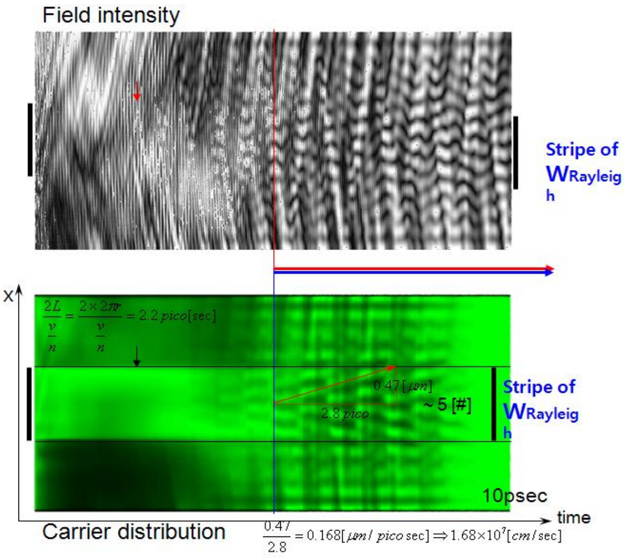

FIG. 2. (a) Intensity profiles $|F|^2+|B|^2$; (b) carrier distributions at z=0 position in the time span of 0 to 10 picoseconds

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