EPSRC GRANT GR/R662889/01 **FINAL REPORT**

Interaction of zero-dimensional electronic and photonic states in semiconductor nanostructures

1 Introduction

This EPSRC research grant was awarded to Professor R A Abram and Dr S Brand of the Department of Physics, University of Durham, and funded a postdoctoral research assistant for three years between 1 August 2002 and 31 July 2005. The project was concerned with the theory of novel photonic microstructures, where localization of light can occur and the light-matter interaction is enhanced due to the localization of light.

The project concentrated on the calculation of the properties of photonic microstructures, where full localization of light can be produced and localized states can be coupled, such as etched Bragg reflectors, opals, coupled microcavities, etc.. Since the original proposal was submitted, progress in the technology of microcavities and quantum dots has allowed the experimental implementation of some theoretical ideas previously expressed by the Durham group. In particular, the strong coupling of exciton and photon states [Kaliteevski et al, *Phys. Rev. B* **64** 115305 (2001)], which was the core of the original submission, has been realized experimentally by two groups [Reithmaier et al, Nature, **432**, 197 (2004) and Yoshieet al, Nature, **432**, 200 (2004)]. This resulted in some change in timing and content of the research programme compared to the original proposal. Substantial attention has been paid to a problem preventing the wider use of photonic microstructures, namely the influence of disorder on their properties.

At the same time there has been considerable international interest in the properties of photonic quasicrystals, and we found we were able to make rapid progress on the theory of such structures. We also collaborated with groups in Germany, France and Russia working on the design of new semiconductor lasers.

2 Research program

2.1 Etched Bragg reflectors

At present, 3D photonic crystals for optical wavelengths are usually produced using self assembly, and the precise engineering of their properties is difficult. It is more desirable to be able to design photonic crystals based on epitaxial growth and etching methods, which are more controllable and well understood. Therefore, we have studied the mode structure and transmission properties of 2D photonic crystals obtained by deep etching of straight grooves perpendicular to the growth direction of a Bragg reflector made from GaAs/oxidized AlAs [1]. We have found that such a structure has a photonic band gap for H-polarized modes. Also, for certain parameters of the etched Bragg reflector, the total density of states is reduced by a factor of 20 compared to that of an effective medium characterized by the averaged relative permittivity.

Our observations are in accord with the results of earlier experimental work in collaboration with colleagues in Berlin and St Petersburg on a novel design of semiconductor laser, with a deeply etched Bragg mirror [2], as shown in figure 1. Incorporation of a deeply etched Bragg reflector can reduce spontaneous emission and improve the Q-factor of the laser mode, which results in an improvement of laser efficiency and optimised geometrical parameters of the output beam, as shown in figure 2. Further work on this approach is planned.

[1] D M Beggs, M A Kaliteevski and R A Abram, Etched Bragg reflectors as two-dimensional photonic crystals, *J. Phys.: Condens. Matter* **16** 8093-8099 (2004)

[2] M V Maximov, E M Ramushina, V I Skopina, E M Tanklevskaya, V A Solov'ev, Y M Shernyakov, I N Kaiander, M A Kaliteevski, S A Gurevich, N N Ledentsov, V M Ustinov, Zh I Alferov, C M Sotomayor Torres, D Bimberg, Edge-emitting InGaAs/GaAs lasers with deeply etched semiconductor/air distributed Bragg reflector mirrors, *Semicond. Sci. Technol*, **17** L69-L71 (2002)

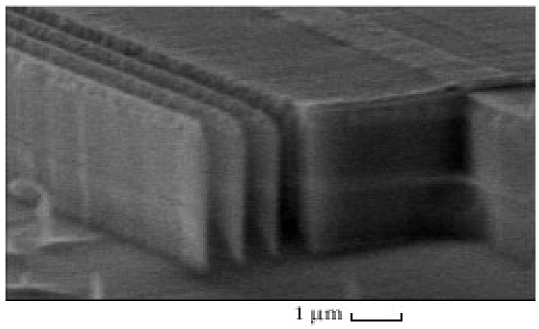


Figure 1. SEM image of a laser with deeply etched air/semiconductor DBR mirror.

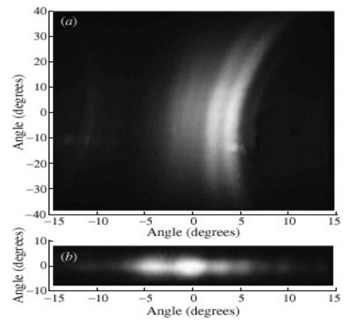


Figure 2. Far-field patterns measured at 200 mA from (a) the cleaved facet and (b) DBR ends.

2.2 Coupled microcavities

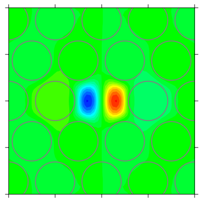
Coupling of two identical quantum oscillators leads to a splitting of their energy eigenvalues, which increases with the overlap of their wavefunctions. In the optical case, the optical modes of two adjacent microcavities can interact through their common mirror, and splitting of the optical mode frequencies is proportional to the amplitude reflection coefficient of that mirror. Increasing the number of coupled microcavities leads to the formation of photonic minibands [3]. Such a miniband manifests itself as a transmission band and we have systematically investigated the properties of a chain of coupled microcavities. It has been shown that for a particular design the structure possesses an almost square transmission band. We have also analysed the conditions of controllable transport of photons in such structures.

A similar situation occurs in photonic crystals of higher dimensionality; for example in hexagonal two-dimensional photonic crystals containing vacancies [4]. Each vacancy is an isolated defect, where light can be localized, and in effect each vacancy acts as a microcavity, as illustrated in figure 2.

We have considered both an ordered periodic (photonic supercrystal) and a random distribution of the vacancies. We have shown that in both cases photonic minibands appear in the former photonic band gaps. The positions of the minibands are defined by the energies of the photonic states localized on the individual vacancies, while the width of the minibands depends on the concentration of the vacancies and the symmetry of the localized photon states. We have proposed that suitably engineered photonic microstructures of this type could be used to produce spectral filters.

[3] D M Beggs, M A Kaliteevski, S Brand, R A Abram, Optimization of an optical filter with a square-shaped passband based on coupled microcavities, *J. Mod. Optics* **51** 437- 446 (2004)

[4] M A Kaliteevski, J M Martinez, D Cassagne, J P Albert, S Brand, R A Abram, Appearance of photonic minibands in disordered photonic crystals, *J. Phys.: Condens. Matter* **15**(6) 785-790 (2003)



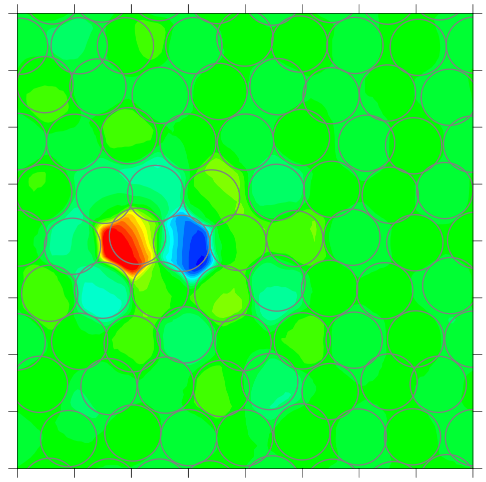


Figure 3. An optical mode localized at a vacancy in an hexagonal photonic crystal (microcavity).

Figure 4. An optical mode localized in an hexagonal photonic crystal in which the cylinders are randomly slightly displaced ("random microcavity"). No individual defect corresponds to a localized state.

2.3 Influence of disorder on the properties of photonic crystals

At present it is impossible to produce an ideal photonic crystal for use at optical wavelengths. The deviation of the sphere diameters in opals and the roughness of the walls in lithographically produced structures lead to departures from the intended periodic spatial distribution of relative permittivity. Such imperfections can damage the photonic band gap (PBG) significantly and result in a finite value of the density of states across the whole of the intended gap. As a result, much effort has been spent on investigations of the influence of disorder on the PBG and the related problem of wave localization in disordered optical media. Surprisingly, a quantitative criterion for the stability of the PBG in the presence of disorder, which is a critical issue for the development of the technology, has not been previously obtained, even for the 1D case, despite the substantial efforts of the scientific community working in the field. Therefore, in an effort to clarify the physical picture of electromagnetic modes in disordered photonic crystals, we conducted *ab-initio* calculations of both the mode structure of the electromagnetic field and the photon transport properties of 1D disordered photonic crystals.

In particular, we analyzed quantitatively the penetration of states into the band gap of a type of one-dimensional disordered photonic crystal [5-7]. We have found that the relative fluctuation of the optical length of the period of the structure can be used as a universal parameter, describing the density of states within the PBG and the transport properties of the system. We have shown that the tail of the density of states in the band gap has a Gaussian form characterized by a penetration depth parameter and that there is an allowed level of disorder below which the probability of the appearance of photonic states at the centre of the photonic band gap essentially vanishes. A relationship between the relative penetration depth, relative gap width and disorder parameter has been found, and a scaling formula relating the attenuation length to the gap width and disorder has also been obtained. The threshold value of the disorder parameter is equal to the square root of one third of the relative width of the PBG. Analysis of the lifetimes of the photonic states allowed us to give a quantitative description of the localization of light.

We have also conducted calculations of the transmission properties and density of states of 2D photonic crystals [8,9]. We have found that like the 1D case, there is a critical level of disorder, below which the states do not penetrate into the PBG. When the disorder exceeds the threshold level, localized states with field profiles similar to those shown in figure 2 penetrate deeply into the PBG.

We have analysed the transmission and reflection of ballistic and scattered light for the case of complete and incomplete PBG structures. For both complete and incomplete PBG structures the dependence of the transmission coefficient at the centre of the PBG as a function of disorder exhibits threshold-like behaviour. The threshold corresponds to the filling of the PBG with localized states. The behaviour of the scattered light is different for the cases of complete and incomplete PBGs. For a complete PBG, ballistic light dominates the transmission spectrum below threshold but above threshold the intensity of scattered light is larger. For an incomplete PBG, scattered light dominates the transmission spectrum, even for small disorder. Another significant result is that the minimum in the transmission spectrum for scattered light does not correspond to the centre of the PBG.

[5] M A Kaliteevski, D M Beggs, S Brand, R A Abram, and V V Nikolaev, Stability of the photonic band gap in the presence of disorder, submitted to *Phys. Rev. Lett.* 2005

[6] D M Beggs, M A Kaliteevski, S Brand, R A Abram, V V Nikolaev, Statistics of eigenmodes in one-dimensional disordered photonic crystals, submitted to *Phys. Rev. B* 2005

[7] M A Kaliteevski, V V Nikolaev, R A Abram, Optical properties and statistics of the eigenstates in 1D disordered photonic crystals, *Physics of the Solid State* **47**(10) (2005)

[8] D M Beggs, M A Kaliteevski, R A Abram, D Cassagne and J P Albert, Disorder-induced modification of the transmission of light through two-dimensional photonic crystals, *J. Phys.: Condens. Matter,* **17** 1781-1790 (2005)

[9] D M Beggs, M A Kaliteevski, S Brand, R A Abram, D Cassagne and J P Albert, Disorder induced modification of reflection and transmission spectra of a two-dimensional photonic crystal with an incomplete band-gap, *J. Phys.: Condens. Matter,* **17** 4049-4055 (2005)

2.4 Localization of light in disordered opals filled with semiconductor nanocrystals

Together with an experimental group at Wuppertal, we have studied experimentally and theoretically the photoluminescence transmission of light in opal in-filled with nanoclusters of CdTe. The transmission measurements suggest that the opal samples exhibit substantial disorder. We have found that within the photonic band gap the photoluminescence is suppressed, but grows faster with increased pumping than outside the photonic band gap. We have attributed this effect to stimulated emission through photonic states localized due to disorder [10].

[10] S G Romanov, M A Kaliteevski, C M Sotomayor Torres, J Manzanares Martinez, D Cassagne, J P Albert, A V Kavokin, F Laussy, V V Nikolaev, S Brand, R A Abram, N Gaponik, A Eychmueller and A L Rogach, Stimulated emission due to light localization in the bandgap of disordered opals, *Phys. Stat. Sol. C* **1** 1522-1530 (2004)

2.5 Photonic quasicrystals

In quasicrystals, which exhibit long-range but non-periodic order, the degree of rotational symmetry can be greater than for crystals, e.g. eight, ten, or even more. Initial theoretical and experimental studies had suggested the presence of omnidirectional photonic band gaps for photonic quasicrystals, but since then some contradictions have emerged between the results obtained by different groups, and a more detailed investigation of the properties of photonic quasicrystals was required. To investigate either of the stopbands observed in photonic quasicrystals, corresponding to complete PBGs, we analyzed the directionality in the reflection and transmission spectra of Penrose-type photonic quasicrystals [11]. In the frequency interval considered, there are two omnidirectional stopbands. It was found that for the low-frequency stopband, light is reflected ballistically, while for the higher frequency band, reflected light is scattered with a change in wavevector equal to one of the reciprocal lattice vectors associated with the first stopband. The relationship between the intensities of the ballistic and the scattered reflected and transmitted light suggests that two-dimensional quasicrystals possess an omnidirectional PBG for the E and H polarizations.

We have also proposed a new type of photonic crystal with a unit cell possessing a local quasicrystalline arrangement of elements [12, 13]. The bandstructure and density of states of various two-dimensional photonic crystals with octagonal quasicrystalline unit cells have been calculated. The presence of PBGs in such structures has been demonstrated and it has been suggested that the band gaps are due to Bragg-like diffraction from planes associated with certain features in the quasicrystalline unit cell. It is also shown that for a small filling fraction, there is a critical size of the unit cell necessary for the establishment of a PBG.

[11] M A Kaliteevski, S Brand, R A Abram, Directionality of light transmission and reflection in two-dimensional Penrose-tiled photonic quasicrystals, *J. Phys.: Condens. Matter*, **16** 1269 -1278 (2004)

[12] D T Roper, D M Beggs, M A Kaliteevski, S Brand and R A Abram, Properties of two-dimensional photonic crystals with an octagonal quasi-crystalline unit cell, accepted for *J. Mod Optics* 2005.

[13] R A Abram, D M Beggs, D T Roper, M A Kaliteevski and S Brand, Photonic band-gap quasicrystals, *Proc. of International Conference on Electromagnetics in Advanced Applications and European Electromagnetic Structure Conference, Torino, Italy* (2005)

2.6 Interaction of an evanescent electromagnetic field with an exciton

The formalism describing the interaction of an exciton of reduced dimensionality with a propagating electromagnetic wave was developed two decades ago. We have now developed a semi-classical formalism to describe the interaction of a quantum well exciton with an evanescent optical wave in the waveguiding regime [14-16]. We have considered structures having a quantum well placed behind an interface at which light experiences total internal reflection or placed in the cladding layer of a planar waveguide. We have obtained an exact solution of Maxwell's equations in the TE and TM polarisations and have given simplified expressions for the effective reflection and transmission coefficients of the quantum well using a generalized Snell law. We have shown that if the angle of incidence corresponds to the critical angle for total internal reflection, the excitonic resonance in the reflection spectrum becomes more pronounced by an order of magnitude compared to that in the normal incidence case.

[14] D M Beggs, M A Kaliteevski, S Brand, R A Abram, V V Nikolaev, and A V Kavokin, Interaction of quantum well excitons with evanescent plane electromagnetic waves, *J. Phys.: Condens. Matter* **16** 3401-3409 (2004)

[15] D M Beggs, M A Kaliteevski, S Brand, R A Abram and A V Kavokin**,** The interaction of quantum well excitons with evanescent EM waves and the spectroscopy of waveguide polaritons, *Physics of Semiconductors, AIP Conference Proceedings* **772** 1166-1167 (2005)

[16] D M Beggs, M A Kaliteevski, S Brand, R A Abram and A V Kavokin, Waveguide polaritons: interaction of a quantum well exciton with an electromagnetic mode of a planar waveguide, *Phys. Stat. Sol. C* **2** 787-790 (2005)

2.6 Additional waves in spherical multilayered photonic structures

In recent years there has been rapidly increasing interest in nanostructured materials where additional electromagnetic waves (i.e. plasmons and polaritons) can appear, such as metallic and composite opals etc. It was therefore timely to develop a rigorous theoretical description of the properties of the "building blocks" of such structures, and multilayered spherical structures in particular. To perform this task we have developed a transfer matrix method for spherical waves in structures where exciton and/or plasmon resonance occurs [17], and are investigating the properties of such systems.

[17] V V Nikolaev, M A Kaliteevski, S Brand, R A Abram and A V Kavokin, Additional waves in spherical multilayered structures, submitted to *Phys. Rev. B*, 2005

3 Dissemination and exploitation

The results have been disseminated to a wide audience in the conventional way through several journal papers and a number of conferences. In addition to the conference proceedings listed on the IGR form, unpublished conference presentations were given at the International Workshop on Solid State Physics in Clermont-Ferrand (France), an EPSRC "Nanotechnology Theme Day" workshop (London), a workshop on Photon-Mediated Phenomena in Nanostructures, Cambridge, and a CMMP Conference at Warwick. We also had discussions with informal collaborators in Montpellier, Wuppertal, St Petersburg, Southampton and Leeds.

4 Personnel

The grant provided funds for a postdoctoral research assistant and 5% of the time of a computer officer for technical support, as well as associated consumables and travel costs. Work on the project began on 1 August 2002 with the appointment of the postdoctoral research assistant who remained for the full three years of the project. An EPSRC DTA-funded research student has also been heavily involved in the project, and working on highly topical problems in close association with an experienced postdoctoral researcher has been an excellent training opportunity for him.

5 Expenditure

The expenditure of the grant did not differ significantly from the requests made in the original proposal.

6 Further research

During the project, the research group gained further experience in the area of artificial photonic materials, and related work is currently underway in connection with an EPSRC-funded project "Artificial materials for terahertz frequency applications". That project is a joint experimental and theoretical investigation involving collaboration between staff in the Department of Physics and the School of Engineering in Durham.