Superradiant Emission from AlInGaAs/InGaAsP Quantum-Well Waveguides

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Abstract—**Superradiant emission from a quantum-well semiconductor structure has been experimentally demonstrated at room temperature for the first time, resulting in a 5MHz train of 390fs pulses with 7.2W peak power at 1580nm wavelength.**

Keywords: Superradiance; femtosecond phenomena

I. Introduction

Owing to its ability to generate ultrashort high power optical pulses, superradiance (SR) has been investigated both theoretically and experimentally [1-3] since the concept was first proposed in 1954 [4]. SR emission has been of particular interest because of its unique properties of femtosecond pulse generation, spatial coherency and large field amplitude. It has shown great potential for many applications such as medical systems, imaging systems, sensing devices and bio-photonics [5]. The main difficulty in obtaining SR emission from semiconductor structures is to attain the extremely high concentrations of the electron-hole (e-h) pairs necessary to achieve an excitonic condensate at ordinary temperatures. This is required to achieve cooperative radiation of the inverted quantum oscillator. Until recently, SR has only been experimentally reported in bulk semiconductor (GaAs/AlGaAs heterostructures) at room temperature at wavelengths around 880 nm [1].

However, in this work, we have for the first time experimentally demonstrated SR emission from a quantum-well device at room temperature. SR is confirmed by analyzing the evolution of the optical spectra, and superradiant trends and regimes are studied as a function of driving condition. A 5 MHz optical pulse train has been obtained in the 1.55 μm wavelength window, with pulse durations as short as 390 fs and pulse peak powers of 7.2 W.

II. Device Description

The active region of the device under investigation, Fig. 1(a), incorporates a 5 AlGaInAs QW active structure which is grown on an InP substrate using MBE. Standard photolithography and ICP dry etch processes are used to fabricate the 3 μm wide ridge waveguide structures. The device is operated at a room temperature of 20 ^{o}C and has an emission wavelength of ~1.55 μm. The back facet is HR coated and the front facet is AR coated. Light is coupled out of the system via the front facet using a lensed fiber. The total length of the device is 1.03 mm, Fig. 1(b), comprising two 415 μm long gain sections and one 200 μm long absorber section. Two gain sections are connected to an electrical pulse generator that has a tunable amplitude from 0 to 2 A, a tunable pulse repetition rate up to 5 MHz and minimum pulse width of 9 ns, whilst a dc reverse bias voltage from 0 to 8 V is applied to the absorber section.

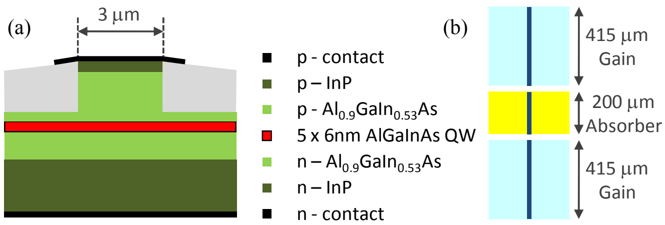

Figure 1. (a) Schematic diagram of the QW waveguide and epitaxial structure; (b) structure of the multi-section design.

III. Experimental Results

In classic SR theory, the properties of SR emission are determined by two fundamental effects: mutual phasing of emitters and the collective spontaneous emission of the correlated emitters. It is shown in [1] that there are three critical criteria to achieve SR emission in semiconductor structures at room temperature: (i) high current pumping, (ii) larger internal carrier density and (iii) high gain, namely the realization of the condition $\alpha L >> 1$, where α is the small-signal gain and L is the length of the structure. These criteria can be experimentally implemented by applying a strong current pulse to the one section of the device. With the other section in a strongly absorptive state, high optical gain can build up and suppress the phase relaxation processes at the early stage of evolution. In turn, this can induce the generation of SR pulses. A pulsed drive current of 0-400 mA is therefore used in the investigated QW structure to increase the inversion of the system and overcome the destructive role the phase relaxation in the early stage of the SR pulse generation. A dc reverse bias from 0 to 8 V is applied to the absorber in order to prevent lasing and achieve higher levels of e-h densities in the structure.

The investigated device has a lasing threshold of 75mA with both gain sections pumped and 0 V absorber applied. However, SR, as a result of simultaneous recombination of a large number of the correlated emitters, can only be observed for currents over 275 mA due to the requirement of high pumping and large carrier density for e-h condensates [6]. As a result strong absorption is required to prevent conventional lasing in the device.

Fig. 2 shows the evolution of SR pulse generation. The drive pulse amplitude is fixed at 400 mA while the reverse bias voltage is varying from 0 to 8 V to control the optical gain profile. Initially, stimulated emission can be observed at lower bias voltage (i.e. low e-h density) in the form of gain-switching and Q-switching. There is a transition between the Q-switching and SR regimes and the optical spectrum drifts dramatically (>20 nm) toward longer wavelength during the transition. This red shift corresponds to the band gap shrinkage as the e-h density increases with the increase in reverse bias. SR emission from an e-h condensate can be observed when mutual phasing of the individual e-h pairs occurs and a coherent cooperative state forms right at the band gap. In contrast to the gain and Q-switching spectra, which exhibit longitudinal modes, the SR spectrum is continuous without any mode structure and hence SR is considered as collective spontaneous emission of the correlated e-h pairs (rather than lasing). The shape of the continuous spectra of the cooperative recombination is asymmetric with the long wavelength edge being steeper than the short wavelength.

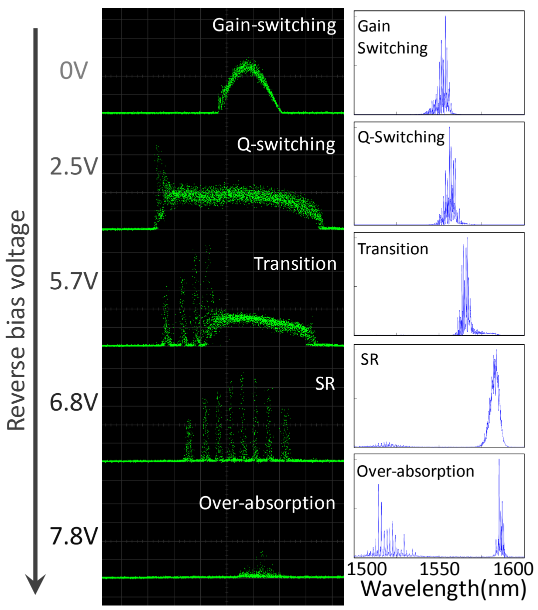

Figure 2. SR pulse evolution: drive pulse amplitude fixed at 400 mA while reverse bias voltage changing from 0 to – 8 V. Pulse development observed from oscilloscope (upper, 1 ns/div.) and optical spectrum analyzer (lower, res. BW = 0.07 nm).

Fig. 3 (a) shows the regimes of SR emission. The device can work in different operating regimes under different driving conditions. A train of single SR pulses with femtosecond pulse duration can be observed for drive currents from 275 to 325 mA while bursts of multiple SR pulses (see Fig. 2) are detected at higher drive currents. Multiple SR pulses can also be observed for electrical drive pulse widths greater than 9 ns for lower drive currents. The individual pulse width however always lies in the hundreds of femtosecond range. The average output power as a function of driving conditions can be seen in Fig. 3(b). The average power decreases rapidly during the transition (along with the associated red shift of the optical spectrum), which leads to a relatively low SR average power.

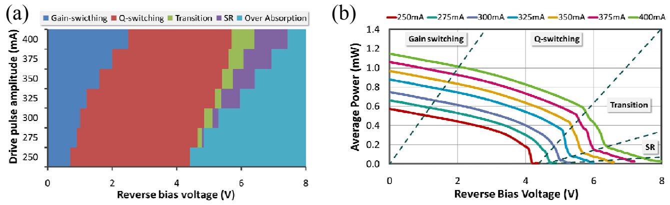

Figure 3. (a) SR regimes and (b) measured average output power as a function of driving conditions.

For optimized SR operation, the gain section is driven at 325 mA, whilst a 5.95 V bias voltage is applied to the absorber section. As shown in Fig. 4(a), a SR pulse is obtained with an optical pulse duration of 390 fs at a pulse repetition rate of 5 MHz. The estimated pulse peak power is 7.2 W with a pulse energy of 3.3 pJ. Fig. 4(b) shows the optical spectrum under such operation. The central emission wavelength is 1583.6 nm, with a spectral width of 3.67 nm. It should be noted that the small peak observed from the shorter wavelength (~1515 nm) corresponds to the spontaneous emission with much higher photon energies in the QW structure.

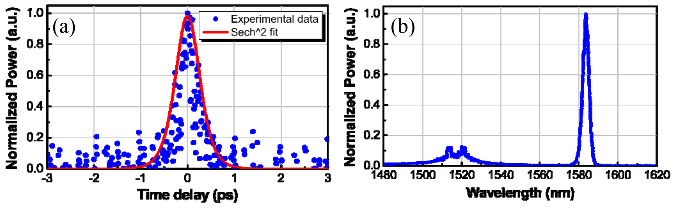

Figure 4. (a) Autocorrelation trace for SR emission under 325 mA driving current and -5.95 V reverse bias voltage; (b) corresponding optical spectrum.

IV. Conclusion

We have experimentally demonstrated superradiant emission from an AlGaInAs quantum-well semiconductor structure at room temperature for the first time. SR trends and regimes have been measured as a function of driving conditions. A 5 MHz SR pulse train has been obtained at an emission wavelength of 1.58 µm, with a pulse width as short as 390 fs and 7.2 W pulse peak power.

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