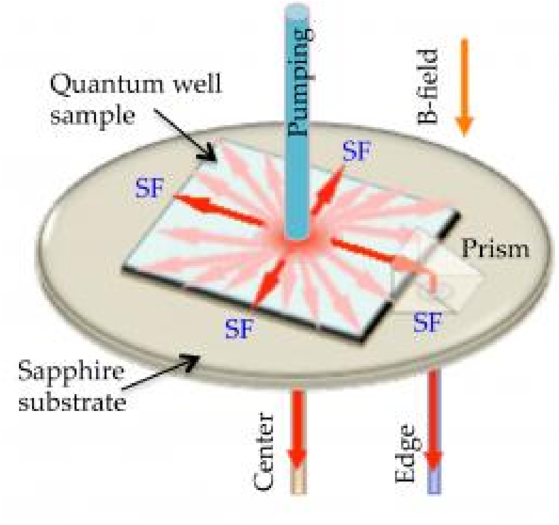
Many bodies make one coherent burst of light: Researchers see superfluorescence from solid-state material

January 30 2012



Pumping laser pulses into a stack of quantum wells created an effect physicists had long sought but not seen until now: superfluorescence in a solid-state material. The Rice University lab of physicist Junichiro Kono reported the results in Nature Physics. (Credit: Tim Noe/Rice University)

In a flash, the world changed for Tim Noe – and for physicists who study what they call many-body problems. The Rice University graduate student was the first to see, in the summer of 2010, proof of a theory that solid-state materials are capable of producing an effect known as superfluorescence.

That can only happen when "many bodies" – in this case, electron-hole pairs created in a semiconductor – decide to cooperate.

Noe, a student of Rice physicist Junichiro Kono, and their research team used high-intensity laser pulses, a strong magnetic field and very cold temperatures to create the conditions for superfluorescence in a stack of 15 undoped quantum wells. The wells were made of indium, gallium and arsenic and separated by barriers of gallium-arsenide (GaAs). The researchers' results were reported this week in the journal Nature Physics.

Noe spent weeks at the only facility with the right combination of gear to carry out such an experiment, the National High Magnetic Field Laboratory at Florida State University. There, he placed the device in an ultracold (as low as 5 kelvins) chamber, pumped up the magnetic field (which effectively makes the "many body" particles – the electron-hole pairs – more sensitive and controllable) and fired a strong laser pulse at the array.

"When you shine light on a semiconductor with a photon energy larger than the band gap, you can create electrons in the conduction band and holes in the valence band. They become conducting," said Kono, a Rice professor of electrical and computer engineering and in physics and astronomy. "The electrons and holes recombine – which means they disappear – and emit light. One electron-hole pair disappears and one photon comes out. This process is called photoluminescence."

The Rice experiment acted just that way, but pumping strong laser light into the layers created a cascade among the quantum wells. "What Tim discovered is that in these extreme conditions, with an intense pulse of light on the order of 100 femtoseconds (quadrillionths of a second), you create many, many electron-hole pairs. Then you wait for hundreds of picoseconds (mere trillionths of a second) and a very strong pulse comes out," Kono said.

In the quantum world, that's a long gap. Noe attributes that "interminable" wait of trillionths of a second to the process going on inside the quantum wells. There, the 8-nanometer-thick layers soaked up energy from the laser as it bored in and created what the researchers called a magneto-plasma, a state consisting of a large number of electron-hole pairs. These initially incoherent pairs suddenly line up with each other.

"We're pumping (light) to where absorption's only occurring in the GaAs layers," Noe said. "Then these electrons and holes fall into the well, and the light hits another GaAs layer and another well, and so on. The stack just increases the amount of light that's absorbed." The electrons and holes undergo many scattering processes that leave them in the wells with no coherence, he said. But as a result of the exchange of photons from spontaneous emission, a large, macroscopic coherence develops.

Like a capacitor in an electrical circuit, the wells become saturated and, as the researchers wrote, "decay abruptly" and release the stored charge as a giant pulse of coherent radiation.

"What's unique about this is the delay time between when we create the population of electron-hole pairs and when the burst happens. Macroscopic coherence builds up spontaneously during this delay," Noe said.

Kono said the basic phenomenon of superfluorescence has been seen for years in molecular and atomic gases but wasn't sought in a solid-state material until recently. The researchers now feel such superfluorescence can be fine-tuned. "Eventually we want to observe the same phenomenon at room temperature, and at much lower magnetic fields, maybe even without a magnetic field," he said.

Even better, Kono said, it may be possible to create superfluorescent pulses with any desired wavelength in solid-state materials, powered by electrical rather than light energy.

The researchers said they expect the paper to draw serious interest from their peers in a variety of disciplines, including condensed matter physics; quantum optics; atomic, molecular and optical physics; semiconductor optoelectronics; quantum information science; and materials science and engineering.

There's much work to be done, Kono said. "There are several puzzles that we don't understand," he said. "One thing is a spectral shift over time: The wavelength of the burst is actually changing as a function of time when it comes out. It's very weird, and that has never been seen."

Noe also observed superfluorescent emission with several distinct peaks in the time domain, another mystery to be investigated.

More information: www.nature.com/nphys/journal/v … t/abs/nphys2207.html

Provided by Rice University

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