Mathematical modelling of the Purcell effect in plasmonic nanostructures

Popular scientific abstract

Nanowires are nanostructures with two of the three spatial sizes typically smaller than 100 nm (sizes of the nanowire cross-section) and the third size typically larger than that (length of the nanowire). Metal nanowires are widely used in nano-science and nano-technology because of their superior electrical and optical, mechanical and thermal properties. In particular, they can be used in nanolasers, which have many potential applications, and in optical computers, for which there is a great demand because they will provide higher processing speeds.

Spherical nanoparticles in nanolasers produce light propagating in all possible directions. As a result the electric field vector of light also has all possible directions. The light of the well defined directions, however, could be used in various important applications. Nanowires have an advantage here, because they are capable of producing light with predominant electric field vector direction along a nanowire axis, contrary to the spherical nanoparticles. This is one of the many examples, why the nanowires are worth studying.

In nanolasers, the nanowires are located close to emitters of electromagnetic waves, such as atoms or particles behaving like atoms. Such closeness changes the way emitters produce electromagnetic waves. For example, an emitter located in free space would produce relatively small amount of trains of electromagnetic waves during one second, that is, it emits waves pretty slowly. If we place this emitter close to the nanowire, or any other object, the produced number of trains of waves per second will change, either increase or decrease, that is, the emission will either speed up or slow down. This effect is called the Purcell effect. The trains of electromagnetic waves produced by an emitter located close to a metal nanostructure propagate on the surface of this nanostructure and are called surface plasmons. Hence, the Purcell effect of the emitter close to the nanowire consists in increase or decrease of the speed with which an emitter produces trains of surface plasmons on the surface of the nanowire.

We numerically study the Purcell effect for a single emitter located near a single metal nanowire. The smaller the metal nanowire is and the closer is the emitter to the nanowire, the larger is the Purcell effect, that is, the larger is an increase or decrease of production of surface plasmons. We study how the Purcell effect changes with the nanowire size. The Purcell effect also depends on the wavelength of electromagnetic wave produced by an emitter. For one particular wavelength it could be stronger and for different wavelength it could be weaker. Additionally, an emitter can produce surface plasmons with different directions of the electric field vector depending on the orientation of the emitter. It turns out that the Purcell effect crucially depends on the emitter orientation. If the emitter is oriented along the nanowire axis, the Purcell effect depends on the wavelength continuously, that is, when the wavelength increases, the Purcell effect becomes gradually stronger, then reaches its maximum and gradually weakens afterwards.

We have found that the situation can be completely different, if the emitter has orientation perpendicular to the nanowire axis. The change of the Purcell effect may then happen in ”jumps”, that is, discontinuously depending on wavelength. We have considered a nanowire with radius of 5 nm and length of 100 nm and an emitter oriented perpendicular to the nanowire axis. As the wavelength changes and reaches particular value, the Purcell effect changes suddenly and abruptly from weak to strong with no gradual, step-by-step change from weaker to stronger. Between such jumps in Purcell effect strength, the change still can happen continuously for intermediate emitter wavelength values. We observe this unusual ”jumping” behavior in our numerical results and explain it by the fact that the emitter produces asymmetric surface plasmons, when the emitter has orientation perpendicular to the nanowire axis. In contrast, in the case of the emitter oriented along the nanowire axis, only symmetric surface plasmons are produced and, therefore, no jumps occur. The found effect can be useful in nanolasers, which have metal nanowires as their functional parts.

Konstantin Filonenko

Life biography

Konstantin Filonenko was born September 22, 1984, in Vladivostok, Russia. In 2001, he entered the Far Eastern State University, the Institute of Mathematics and Computer Science. In connection with his move to St. Petersburg he entered the St. Petersburg State University Department of Physics, Department 'Quantum Electronics'. In 2011, he defended his master thesis on the topic of 'Spectral one-frequency and two- frequency purity of OPO radiation'. In 2011, he entered PhD school at the Department of 'Quantum Electronics' of St. Petersburg State University. The topic of the research work conserned non-classical properties of light. In 2012, he was accepted into PhD school at Syddansk Universitet and has been working at Mads Clausen Institute, Snderborg, from March, 16 of 2012 to March, 15 of 2015 as a fellow researcher. The study program was extended until September, 15 of 2015 and was finished by writing of the thesis. The theme of the thesis is 'Modelling of the Purcell effect in plasmonic nanostructures.' Scientific advisors were Vladimir Bordo and Morten Willatzen. During the project studied plasmonic nanowires and nanowire laser. In addition to the scientific and research work, he showed an interest in teaching, methods of teaching. During the project made oral presentations at the conferences in Stockholm, Sweeden, Hangzhou, China, have presented a poster in London, United Kingdom and Jerusalem, Israel.