

NANOLASER SUPERRADIATION IN INFORMATION AND MEASURING PROCEDURES*

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The subject of the paper is superradiance of nanolasers and its process of quantum dot formation, increased concentration of non-equilibrium charge carriers, as well as physical principles of nanolasers operation with superradiance in telecommunication systems. The objective of the paper is to substantiate the possibility of using nanoscale lasers in the superradiance mode and the devices on their basis to solve problems of transmission of high-speed optical information signals and tasks of the radiation frequency stabilization. Review of several types of nanolasers is performed. It is determined that despite the creation of a number of designs, a general theory of stabilizing the parameters of nanolaser radiation is not developed. It is a deterrent to the development of this type of lasers and their practical application. To use nanolasers in information-measuring procedures, the problems of stabilizing the radiation frequency, obtaining pulses of a predetermined duration (of the femtosecond order), and the peak power must be solved. To provide pulsed radiation with the necessary parameters, the authors propose to use the superradiance mode previously discovered in semiconductor heterostructures and expressed in a sharp increase in the radiation power. The analysis of the conditions for the formation of superradiance in the domain structure of semiconductors is based on the theoretical model for describing the concentration of non-equilibrium carriers (electrons and holes) in the active region of the laser. The process of occurrence of superradiance in nanolasers and the possibility of using this effect are considered. It is proved that high-power femtosecond pulses are formed in nanolasers with superradiance. The results of the carry out studies substantiate the possibility and prospect of using nanolasers in the mode of superradiance and the devices on their basis for transmission of high-speed optic information signals, creation of new optical frequency standards and photonics devices. Their application will contribute to the development of nanometrology, nanotechnology, information and other technologies. Calculations are performed to prove that in the superradiance mode, nanolasers generate the femtosecond pulses with a power of 10.9 μW , which allows the signal to be transmitted along the optic fiber to the distance of 750 m. In the future, works are planned to increase the power of such lasers to transmit information for the longer distances.

KEY WORDS: *nanolaser, superradiance, frequency stabilization, photonics, generation of radiation*

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1. INTRODUCTION

Development of optical nano-objects, primarily, the nanolasers represents one of the most promising trends in development of photonics and laser technologies. Local processes of excitation of plasmon oscillations (the plasmons) on the surface of metal nanoparticles [1] are used in the nanolasers or spasers (the acronym from *Surface Plasmon Amplification by Stimulated Emission of Radiation*).

The existing designs of nanolasers can be subdivided into several groups, in which different mechanisms are used for pumping the active medium. First publications about creation of the nanoscale lasers are dated by the year 2007 (M. Hill, Technical University of Eindhoven, the Netherlands). The first metal-semiconductor nanolaser with the pulse radiation mode was described in the paper [2]. Due to its post-shaped structure the Hill's laser got the name of *Goldfinger*.

In 2011 K. Ding and his colleagues suggested the nanolaser operating in the constant radiance mode under the room temperature [3]. The laser had the dimensions $0.34 \times 3.0 \times 1.53 \mu\text{m}$, electrical pumping, radiation wavelength $\lambda = 1554 \text{ nm}$, the radiation line width 4 nm, the Q -factor of $Q \sim 400$ and high power losses. In 2012 the authors managed to decrease the losses due to increasing the thickness of the silicon nitride shell up to 30 nm [4]. The new laser had the dimensions of $1.15 \times 1.39 \times 1.7 \mu\text{m}$ and the radiation line width of 0.54 nm.

The coaxial nanolaser with optical pumping is represented in the paper by M. Khajavikhan [5]. A group of researchers headed by S. Feynman (California State University, San Diego) developed two structures: 1) with the core diameter and the shell thickness of 100 nm; 2) with the core diameter of 175 nm and the shell thickness of 75 nm. There are publications on creation of even more "compact" nanolasers with the shell thickness of 22 nm [6].

There are known the structures based on the microdisc resonator, in which the whispering gallery modes are excited, and the lasing fills in the inner space of the microdisc. Another structure envisages application of linear semiconductor active media, in which the frequency of generated radiation is determined by spectral properties of the liquid active medium. It is natural that a radiation mechanism of its own is implemented in each of the above options.

However, the structures of almost all the nanolasers are far from being completed due to a number of reasons. The resonator Q -factor at the spasers is low: $Q \sim 15$ for the devices providing for the mode localization within three dimensions, $Q \sim 120$ is at the two-dimensional localization [7]. Whereas the Q -factor of the standard laser resonator amounts to the value of the order of 10^5 [8]. The conditions of formation of spectral and frequency characteristics of radiation of the nanolasers are not determined by now as well; and there is no full understanding of the conditions of their pulse and continuous radiation.

The nanolasers represent a promising trend of development of the nanophotonics. It is solved the problem of applying the nanolasers as the medical tools, time-measuring devices and as the new optical standards of frequency. The nanolasers may be used for creation of the quantum computer elements. The unsolved problem of

formation of the SR pulse is stipulated spontaneously by synchronized phases of separate radiating dipoles included into the domain. Initial stage of increasing of the radiation power is determined by the constant value of the increment. The nanolaser radiation power is increasing based on the exponential law:

$$P = P_0 \exp(yt), \quad (1)$$

where P_0 is the radiation power at the initial moment of time; y is the increment depending on the difference in population of the levels N_1 and N_2 , i.e.,

$$y = \nu \frac{N_1 - N_2}{N_2}, \quad (2)$$

where ν is the normalizing coefficient with the dimensionality of c^{-1} .

From the correlations (1) and (2) at the initial moment of time $t = 0$ it follows that the power of radiation is equal to P_0 , i.e., the level of spontaneous radiation. Further increase of the radiation power is determined by the time dependence N_1 . With the increase of the radiation power the power level population decreases and the process of growth is decelerated, as the result of what it is stabilized the level of the radiation power at a certain moment of time, which level characterizes the maximum level of the pulse radiation. The exponential growth of the lasing power occurs at a large difference between the populations of the operating levels.

The performed analysis of the conditions for the formation of SR in the domain structure is based on the theoretical model for describing the concentration of non-equilibrium carriers (electrons and holes) in the active region of the laser. With the increase of concentration of non-equilibrium carriers and at attaining a certain critical value (n_0) the system is separated into the domains. Therefore, it occurs the non-equilibrium phase transition of the second kind. The domains are represented by stable formations, each of which is a region of the quantum well, where the radiation is localized. Every domain represents a denser optic medium. It can be assumed that within the limits of a single domain there occurs an effect of the “distributed feedback” type resulting in the fact that the domain radiates coherently (all the emitters inside of the domain are in the same phase), as an integral structure. It is just the above spontaneous phasing of the radiating carriers without any external coherent influence on the system is the distinctive feature of the Dicke SR [15].

The nanolasers operating in the continuous or pulse modes can be used as the alternative option to the vertically radiating [16], quantum cascade [17], lasers with the microdisc resonators [18] and fiber lasers [19-21] applied in the information and measuring systems nowadays. The power of the above lasers is commensurable but their spectral and frequency parameters might differ essentially. Application of the nanolasers may exert a positive influence on the temporal mode of operation of the information systems. However, the developments of nanolasers at the level of

industrial prototypes are not available yet. For that reason, the problem of serial use of the nanolasers not only in the information networks, but also in the present-day measuring and sensor devices, still remains important. Attaining of the SR modes in nanolasers is regarded as one of the preconditions for their practical application.

4. PECULIARITIES OF RADIATION OF THE NANOLASERS PROVIDING FOR THE INFORMATION AND MEASURING PROCEDURES

Development of the measuring laser equipment is based on the precision properties of the laser, which properties include the frequency stability that allows determining the parameters of physical values by means of the frequency or time measurements. Similar requirements set to the spatial parameters of the radiation have to be complied with within the limits providing for the required measuring accuracy. Obtaining and stabilization of the necessary value of the nanolaser power is an important condition. The energy of the pulse must be sufficient for traveling along the distance of the device optic fiber and recording with the help of the photodetector.

The peculiarity of information parameters of the nanolasers is in the structural characteristics of the resonator and active medium. The conditions for frequency stability are not established and the radiation beam parameters are not determined in the ring nanolasers with plasmon pumping of the active medium. Therefore, the conditions for the radiation frequency (or the wavelength) stabilization and implementation of a stable radiation pattern must be established based on the examples of the above nanolasers.

The paper [22] provides the estimate of the nanolaser radiation line half-width 0.05...0.07 nm, which is recorded with the help of the *FHR* 1000 monochromator and the multichannel cooled photodetector with the resolution of 0.05 nm, although the above estimate of the radiation line width is restricted by the spectral resolution of the used device and is not the final one.

This situation is quite possible when the diffraction monochromator and not the heterodyne is used for measuring of the radiation line. Therefore, it is necessary to apply the heterodyne method for measuring the radiation line width of the nanolasers considering the divergence of the laser radiation. The classical problem of measuring the radiation line width in relation to the nanolasers is represented by an independent engineering problem, which has to be solved under the conditions of the nano-sized structures.

Duration of the pulse radiation plays an important role in the telecommunication systems and the information-measuring systems. This parameter is comparable in its value with the duration of the ultra-short pulse in the femtosecond laser; and, therefore, the autocorrelation method for analysis of duration of the ultra-short optic pulses developed for measuring the ultra-short radiation pulses of the femtosecond lasers, must be used for its measurement. Estimations of the pulses in the SR modes were performed in the papers [5,6]; and it was shown that the maximum duration limit amounts to 400 fs. Therefore, the SR mode of the nanolasers allows obtaining the femtosecond pulses.

proportional to $(NV)^2$ [4]. In this case, the signal is recorded at the nanolaser radiation power of $P_1 = 10.9 \mu\text{W}$, and according to the expression (4) the range of the signal transmission along the single-mode optic fiber would amount to $L \approx 750 \text{ m}$.

5. CONCLUSIONS

Thus the results of performed investigations provided a basis for the whys and wherefores of the possibility and perspective of using nanolasers in the mode of superradiance and the devices on their basis for transmission of high-speed optic information signals. Their application would facilitate development of nanometrology, nanotechnology, information and other technologies.

A review of several types of nanolasers is performed. It is shown that absence of the general theory of creation and stabilization of radiation parameters of the nanolasers is the factor that impedes their development and practical application. It is noted that the pulses of predetermined length and power, realizable in the SR mode, must be obtained in order to use the nanolasers during the information and measuring procedures.

The calculations are performed proving that the nanolasers in the SR mode form the femtosecond pulses with the power of $10.9 \mu\text{W}$ that allows signal transmission along the optic fiber link to the range of 750 m.

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