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PHOTONIC CRYSTAL NANOLASERS AS OPTICAL FREQUENCY STANDARDS

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Using of the nanolasers with the system of radiation frequency stabilization for development of the nano-size order optical frequency standards is considered in this paper. A number of nanolaser designs, their radiation processes and frequency stabilization are examined. The quantum dot nanolaser model with the wavelength of $\lambda = 633$ nm is developed. Radiation frequency stabilization is performed with the help of the iodine molecules placed into the photonic crystal cell having the T-shaped defect.

KEY WORDS: *nanolaser, optical frequency standard, photonic crystal cell, radiation spectrum, frequency stabilization*

1. INTRODUCTION

Creation of the nano-dimensional devices used for transmission and processing of highly-stable optical information signals [1-7] is one of the scientific and engineering problems solved by modern nanophotonics. These devices include the nano-dimensional optical frequency standards (OFS) created on the basis of the nanolasers (NL) [8-10].

The lasers, which are used as OFS, are characterized by a high degree of the radiation frequency stability and reproducibility. At that, the researchers and developers of NL are busy with solving, primarily, the problem of obtaining the maximum power of radiation with preserving the coherence [11,12]. The radiation frequency stability and reproducibility was considered just in a number of separate cases [13]. Due to the necessity of development of the nano-dimensional optical frequency standards there occurred the problem of creation of the NL with high radiation frequency stability.

The objective of this paper is creation of the model of the quantum dot laser with the radiation frequency stabilization system. In order to attain the set objective the following problems must be solved: the prospects for OFS development are considered; a number of NL designs, processes of their radiation and frequency

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stabilization are examined; it is developed the model of the quantum dot (QD) NL with the radiation frequency stabilization with the help of the iodine molecules placed into the photonic crystal cell.

2. FREQUENCY STANDARDS

The first frequency standards (in the radio frequency range) appeared in 1930s-1940s. Studying the super-subtle structure of the substances selected as the frequency references – quartz, hydrogen, rubidium and cesium – was the precondition for their creation. These standards possess rather bulky dimensions that represents a problem at using them in modern precision instruments.

In 1960s, after creation of the lasers there appeared the OFS based on the single-frequency and single-mode gas lasers stabilized on the basis of the frequency reference points. The first OFS were represented by He-Ne-, Ar- and CO_2-lasers with internal and external absorbing cells, the dimensions of which are either commeasurable with or much more larger than the dimensions of the lasers [5].

By 2000s there were developed the frequency standards using the atoms and ions cooled practically to the absolute zero. Presently, almost a half of the OFS, which are recommended by CIPM [1], use the frequency references based on the cooled atoms and ions retained within the magneto-optic trap [2] or in the optical molasses [3].

The standard relative uncertainty of the OFS radiation frequency is not exceeding the value of the order of 10^{-15}. This condition satisfies most of the research and practical problems [14,15]. However, it is still impossible to perform both improvement of the radiation frequency stability and to substantially diminish the OFS dimensions simultaneously. Therefore, the design features and dimensions of OFS do not allow applying them in the micro- and nano-dimensional information and measuring systems.

The promising trends of the OFS development are related directly to the processes of miniaturization of the laser sources and frequency references. Micro- and nano-technologies are main direction in development of miniature lasers.

Creation of OFS on the basis of NL represents an engineering problem, which includes both creation of the laser properly and of the frequency reference [16]. The authors of the paper [4] are of the opinion that creation of the photonic crystal NL, the defect of which contains single cooled atoms or molecules stabilizing the radiation frequency, is a perspective trend. Trapping of the cooled atoms and their control within the photonic crystal defect was performed by the fields formed in the said defects [5].

3. MECHANISM OF NANOLASER FREQUENCY CONTROL

There exist five of the most widely known types of NL [17]. The basis of the first type (the “plasmon grating”) is formed by the photon-plasmon excitation. This phenomenon is considered as the physical basis of the next generation of information technologies when the photons and not electrons will be basic elements of the memory storage [18].

NL of the second type consists of a set of the metal nanoparticles surrounded by the amplifying medium consisting of organic molecules excited with the help of the incoherent light.

The NL based on the nanofiber made of the cadmium sulfide positioned on the silicon substrate [19] can be referred to the third type.

Type four is represented by the quantum dot (QD) NL acting as the active medium. The resonator of this laser is represented by the metal nanoparticle. The radiation wavelength of the NL on the basis of QD corresponds to the wavelength of the plasmon resonance, which is determined by the metal and shape of the nanoparticles. Thus, silver provides for the blue color of the radiation spectrum, gold – for the green, and copper – for the red. Such NL can be placed in the pores of the thin film of the photonic crystal, the mission of which is in decreasing the laser generation threshold and formation of the NL directed radiation.

The fifth type is represented by the liquid NL. The basis of the liquid NL is represented by the "optical cavity" – the trap, into which the photons from the pumping source hit. The hollow of this cavity is filled with golden nanoparticles having a high value of the reflection factor. The light circulating inside of the optical cavity is concentrated in the places of accumulation of the nanoparticles, where it is focused and amplified. Due to the above approach liquid NL needs no mirrors and other elements inherent to traditional lasers.

Next stage of development of the theory and practice of creation of the NL includes development of the NL frequency stabilization principles, which are common to the lasers of various designs. The above principles have to provide for the following – selection of the efficient radiation frequency control mechanism and formation of the maximally narrow radiation pattern. The most perspective methods for controlling the NL radiation frequency can be separated. The first method comprises tuning of the NL radiation frequency using the photonic crystal periodic structures. An example of such tuning by means of variation of the photonic crystal periodic structure is shown in Fig. 1.

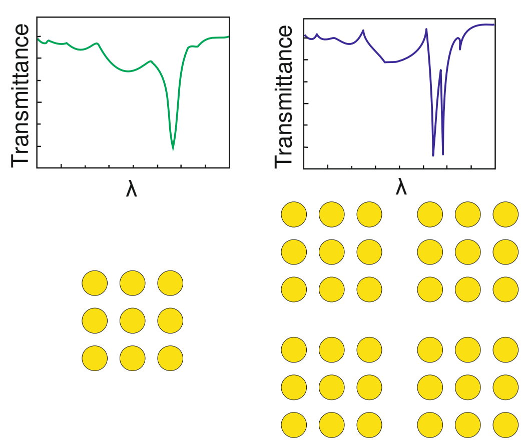

FIG. 1: Periodic structures and correspondent to them radiation spectra

As it can be seen from the results of the modeling (Fig. 5), the NL radiation is concentrated within the photonic crystal defect. Radiation output beyond the boundaries of the photonic crystal defect is restricted by the prohibited zone for $\lambda = 633$ nm. Due to the concentrated field it is possible to perform trapping of the particles in the defect with the Lorentz forces and retaining of the particles with the help of the Casimir-Polder forces. The particles placed into the defect are used for the NL radiation frequency stabilization.

Thus, the presented model of NL on the basis of QD with the radiation frequency stabilization system representing the photonic crystal with the defect containing the iodine molecules, will allow obtaining nano-dimensional OFS for the information and measuring systems.

5. CONCLUSION

Application of the nanolasers with the radiation frequency stabilization system for creation of the OFS is considered in this paper.

A number of the nanolaser structures, processes of their lasing and frequency stabilization are studied. It is proven that the principal problem while using the nanolasers is related to the possibility (or impossibility) of controlling the radiation frequency.

It is developed the model of the quantum dot nanolaser having the wavelength of $\lambda = 633$ nm with the radiation frequency stabilization with the help of the iodine molecules placed into the photonic crystal cell having the *T*-shaped defect.

Mathematical simulation is performed for propagation of the radiation with the wavelength of $\lambda = 633$ nm in the photonic crystal. The results of the simulation confirm the possibility of using the suggested design for the nanolaser frequency stabilization.

The results of the paper would allow developing nano-dimensional optical frequency standards for the information and measuring systems.

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