Directional luminescence of the diamond NV center via Bloch surface waves in one-dimensional photonic crystals

A A Bragina\textsuperscript{1}, K R Safronov\textsuperscript{1}, V O Bessonov\textsuperscript{1,2}, A A Fedyanin\textsuperscript{1}

\textsuperscript{1} Quantum Electronics Department, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
\textsuperscript{2} Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Moscow 119071, Russia
E-mail: bragina@nanolab.phys.msu.ru

Abstract. In this work, we numerically study the luminescence of nanodiamonds with NV centres embedded in a polymer layer on the surface of one-dimensional photonic crystal. The interaction of NV center spontaneous emission with the Bloch surface wave (BSW) is demonstrated. The presence of a photonic crystal leads to a change in the angular distribution of the emitter radiation due to the coupling of luminescence to BSW. We show that the best coupling efficiency of 71% is observed when NV centres are located in the close proximity to the BSW field maximum.

1. Introduction
In recent years, the field of nanophotonics aimed at the control over spontaneous emission of light at the nanoscale level has been actively developed, which is widely used in optical communications, sensing and integrated optics\cite{1}. Various systems have already been studied to control spontaneous radiation, including waveguides made of various materials and two-dimensional photonic crystals with defects\cite{2}. One of the most promising approaches is based on surface electromagnetic waves, since they provide field localization near the surface where radiation sources are located, resulting in luminescence enhancement. The most studied class of such waves is surface plasmon-polaritons (SPP) propagating along metal-dielectric interface. SPP allows achieving significant luminescence enhancement due to the sub-diffraction localization\cite{3} and high Purcell factor. However, they have a number of disadvantages, such as a short propagation length due to Ohmic losses in metal and fixed dispersion law determined by the material of the metal film. These shortcomings limit applications of SPP and lead to research of alternative types of surface waves. One of the most promising type is Bloch surface waves (BSW) propagating on the interface between one-dimensional photonic crystal (PC) and dielectric. Important advantages of BSW over SPP are flexibility of the dispersion law controlled by PC layers materials and thicknesses, as well as the existence of both TE- and TM-polarized waves. In addition, BSW have a large propagation length (of order of 1 mm versus several tens of micrometers for the SPP) due to the absence of Ohmic losses in the dielectric\cite{4}. These advantages have led to the development of various applications, including enhancement of spontaneous emission near the PC surface\cite{5, 6} and integrated photonics\cite{7}. In this work, we...
study luminescent sources integrated into a slab BSW waveguide. This study reveals the BSW potential for on-chip realization of linear and quantum optical circuits.

One of the most promising candidates among sources for integrated photonics are the color centres in diamonds because they are bright stable sources even at the room temperature. Moreover, a family of diamond color centres based on group-IV elements in the periodic table, i.e. nitrogen-vacancy (NV), germanium-vacancy (GeV) and silicon-vacancy (SiV) centres, have attracted attention due to their structural symmetries, leading to high emission into zero-phonon line (ZPL)[8]. These sources have already been successfully integrated into SPP waveguides[9].

This work presents the results of 2D calculations of the emission of an NV center in diamond embedded into a polymer layer on the surface of 1D PC. Calculations were performed by the Lumerical FDTD. The NV diamond is modelled as an oscillating electric dipole. Emission wavelength is $\lambda = 637$ nm matching NV ZPL. We study dependence of coupling efficiency between source and BSW on the source position.

2. Results and discussion

2.1. Model

In 2D FDTD simulation, the 1D PC was modelled as a rectangular structure consisting of five pairs of alternating SiO$_2$ ($n_{SiO_2}=1.46$) and Ta$_2$O$_5$ ($n_{Ta_2O_5}=2.08$) layers with thicknesses of 140 nm and 98 nm, respectively, where top layer is Ta$_2$O$_5$. The PC is located on a glass substrate ($n_{glass}=1.52$) with a thickness of 2 $\mu$m. BSW is not sustained on a bare PC surface. In order to enable excitation of TE-polarized BSW, the PC surface is covered with a 200 nm thick polymer layer of SU-8 photoresist ($n_{SU8}=1.58$). We study the coupling between the NV center located inside the polymer layer and BSW. NV center was modelled as a dipole source emitting at $\lambda = 637$ nm with the dipole momentum lying parallel to the PC surface. At this $\lambda$, BSW effective refractive index, defined as the ratio of BSW propagation constant and vacuum wavenumber, is equal to 1.15. The simulation volume was enclosed by Perfectly Matched Layers (PML).

2.2. Calculations

First of all, the electric field profile of BSW was calculated (Fig. 1a). BSW is localized inside the polymer layer and attenuates inside PC with oscillations. Then coupling efficiency between the source and BSW was studied. For this purpose, we calculated the field distribution at a distance of 10 $\mu$m from the dipole source and then estimated the overlap integral of this field and the BSW field. Coupling efficiency is a fraction of source radiation transmitted into BSW mode. We calculated the coupling efficiency using Mode Expansion Monitor in Lumerical FDTD. The result showing efficiency dependence with respect to the source position in the polymer layer is shown in Fig. 1b. It demonstrates that the efficiency significantly depends on the source position. The maximum efficiency of 71% is observed when the dipole is placed at h=154 nm inside the 200 nm polymer layer. The obtained value corresponds to the position of BSW field intensity maximum. For the obtained optimal source position, the angular distribution of the dipole emission intensity in a far-field was calculated (Fig. 2a). For this purpose, the dipole radiation intensity was calculated with the use of two Frequency-domain Profile and Power Monitors parallel to the surface of the PC: one located above the PC and the other placed inside the polymer film under the dipole. The intensity maximum occurs at the angles of $\theta = -46.77^\circ$ and $\theta = 226.77^\circ$. These angles correspond to the effective refractive index $n_{eff} = n_{SU8} \sin \theta = 1.15$. The $n_{eff}$ of radiation is equal to BSW $n_{eff}$. Thus, the radiation direction is related to the excitation of BSW. The results demonstrate that NV center coupled with BSW has directional luminescence. Fig. 2b shows field intensity distribution of NV center emission inside the PC. Almost all of the source radiation is guided inside the polymer layer, which acts as a BSW waveguide. Noteworthy, dipole with polarization perpendicular to PC surface does not couple with BSW, since only TE-polarized component of field can couple with BSW.
3. Conclusion
In this work, we performed numerical calculations of the emission from a diamond with NV center located in the polymer film on the PC surface, supporting the BSW propagation. We have shown that dipole spontaneous radiation becomes directional when coupled with BSW: the radiation intensity becomes sharply distributed at certain angles and the emission is localized in the polymer layer. In addition, the coupling efficiency between the NV center and BSW was calculated and the source position corresponding to the maximum efficiency of 71% was determined. Spontaneous emission coupled with BSW in PC is very attractive for future applications in on-chip photonic circuits.
4. Acknowledgments
This work was supported by MSU Quantum Technology Centre and the Russian Foundation for Basic Research (grant №19-32-90225). The research was performed according to the Development program of the Interdisciplinary Scientific and Educational School of Lomonosov Moscow State University ”Photonic and Quantum technologies. Digital medicine”.

References
[1] Dubey R, Barakat E, Häyrinen M, Roussey M, Honkanen S K, Kuittinen M and Herzig H P 2017 Journal of the European Optical Society-Rapid Publications 13 1–9
[2] Aharonovich I, Enghard D and Toth M 2016 Nature Photonics 10 631–641
[3] Sederberg S, Firby C J, Greig S R and Elezzabi A Y 2017 Nanophotonics 6 235–257
[4] Meade R D, Brommer K D, Rappe A M and Joannopoulos J 1991 Physical Review B 44 10961
[5] Stella U, Boarino L, De Leo N, Munzert P and Descrovi E 2019 ACS Photonics 6 2073–2082
[6] Soboleva I, Descrovi E, Summonte C, Fedyanin A and Giorgis P 2009 Applied Physics Letters 94 231122
[7] Abrashitova K A, Gulkin D N, Safronov K R, Kokareva N G, Antropov I M, Bessonov V O and Fedyanin A A 2018 Applied Science 8 63
[8] Siampour H, Kumar S, Davydov V A, Kulikova L F, Agafonov V N and Bozhevolnyi S I 2018 Light: Science Applications 7 1–9
[9] Siampour H, Kumar S and Bozhevolnyi S I 2017 ACS Photonics 4 1879–1884