IEEE MTT-S Pre-Graduate Scholarship Project Report

Electromagnetic Engineering of Optical Nanowire Sensors for Electron Beam Diagnostics

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***Abstract* — We study the diffraction radiation that occurs if a modulated beam of electrons flows near a pair of identical circular dielectric and silver nanowire scatterers, in the visible wavelength range. Such a pair of nanowires behaves as two optically coupled open resonator, thanks to which the diffraction radiation is enhanced near the wavelengths of the natural modes. We have computed spectral characteristics of this resonator, visualized the far field patterns, and analyzed their dependence on electron beam parameters.**

***Index Terms* — diffraction radiation, dielectric nanowires, total scattering cross-section, resonances on supermodes**

I. INTRODUCTION

As it was found in the 1950s, the electrons passing nearby a periodic structure, say, a lamellar grating, radiate the light. This effect obtained the name of its discoverers, Smith and Purcell. Today, it is considered as a particular case of more broadly defined effect: the diffraction radiation (DR) of the surface and polarization currents induced on various material objects by the charged particles or their beams, which do not touch or hit these material objects.

Detection of DR in the visible wavelength region, also called the optical DR, is the most promising technique for application to noninvasive beam diagnostics. Therefore, our goal is exploration of the opportunity of using the configuration in Fig. 1 for the measurement of the DR power characteristics and obtaining the information on the beam position shift h.

Nanoscale size of such DR sensor antennas introduces negligible distortion to the beam energy characteristics, which can be considered as fixed. This makes possible the analysis of the DR in the same way as within the traditional electromagnetic theory, i.e. as the scattering of the given electromagnetic field of the moving beam by the scatterers of given shapes and material properties.

II. NUMERICAL RESULTS

Fig. 2 demonstrates the wavelength scans of TSCS (total scattering cross section) for thick silicon nanowires ($\varepsilon = 12$) with radius a = 200 nm. As one can see, in this case there are many resonances within the visible range (i.e. for the wavelength from 300 nm to 800 nm). What is more interesting, if the relative velocity of the beam is 0.5 or smaller and it flows with a shift ($h \neq 0$), then the resonance peaks split into pairs of closely located doublets.

The reason of split is the optical coupling between the natural modes of individual wires. For a stand-alone wire, all non-axially symmetric modes are double degenerate thanks to the circular symmetry. If the second wire appears, then this degeneracy is removed. Additionally, each of these no more degenerate modes can make a bonding or anti-bonding couple with the similar mode of the other wire. Therefore the modes of the twin wires are called "supermodes" and are classified using two additional indices, showing the parity with respect to the symmetry lines (in our case, the axes x and y, see Fig.1). Close inspection shows that the modes (complex poles) underlying the peaks of TSCS at the wavelengths of 326 nm and 328 nm in Fig. 3, corresponds to the supermode $H_{6,2}^{oo}$ and apparently not resolved sister-modes $H_{6,2}^{eo}$, $H_{6,2}^{oe}$, $H_{6,2}^{ee}$, respectively. Similarly to that, two sharper peaks at 329 nm and 330 nm correspond to the high-Q supermode $H_{9,1}^{oo}$ and three not resolved sister-modes $H_{9,1}^{eo}$, $H_{9,1}^{oe}$, $H_{9,1}^{ee}$, respectively. This interpretation is supported by the far-field radiation patterns, shown in Fig. 4, for non-symmetric excitation of twin wires wires. In Fig. 5, the near magnetic field patterns for the same peaks of TSCS as in Fig. 4 are presented.

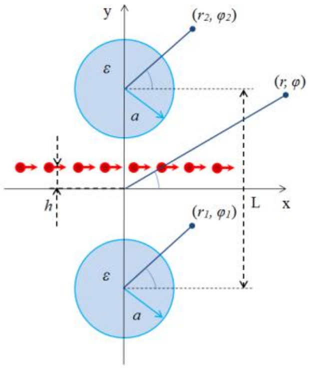

Fig. 1. Cross-sectional geometry of an electron beam moving between a pair of identical circular nanowires.

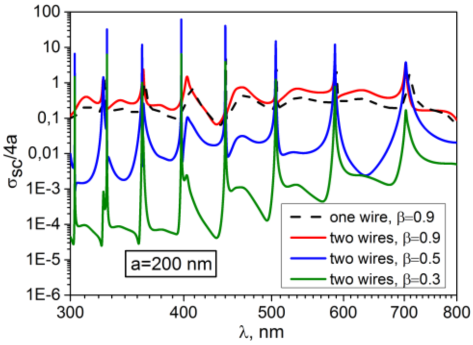

Fig. 2. Normalized TSCS of the 200-nm in radius one (dashed curve) and two silicon nanowires versus the wavelength in the visible range, for several values of the electron relative velocity β.

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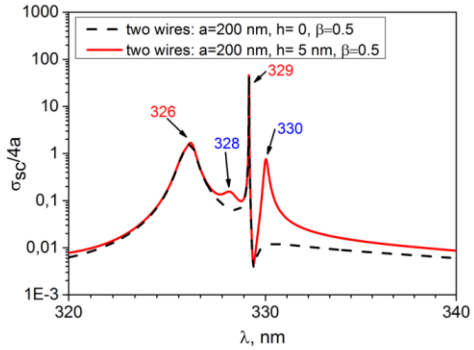
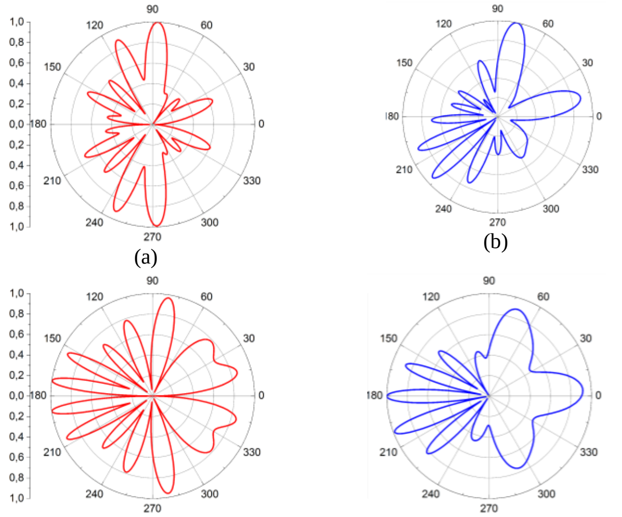


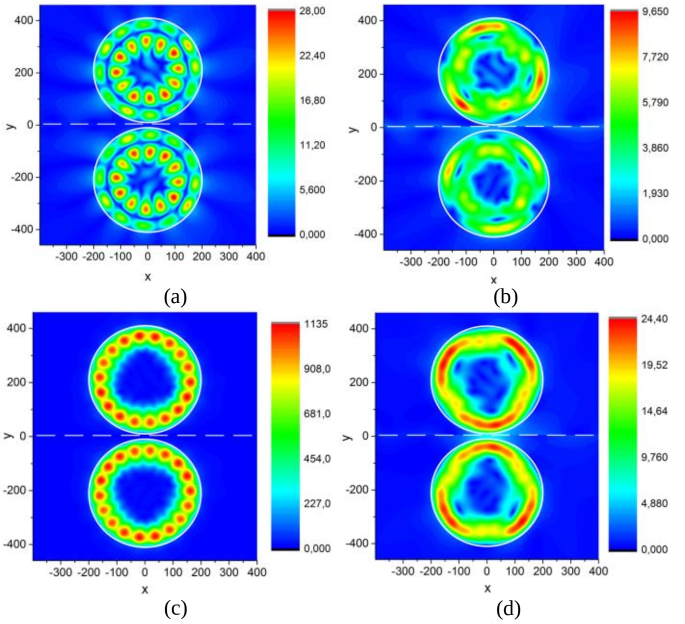
Fig. 3. Normalized TSCS of two identical 200-nm in radius silicon nanow versus the wavelength, for the electron relative velocity $\beta = 0.5$ and values of the shift distance h.



(a) (b)

(c) (d)

Fig. 4. Non-symmetric excitation. In-resonance far-field patterns for h = 5 nm and β = 0.5 at λ = 326.16 (a), 328.13 (b), 329.15 (c) and 330.03 nm (d).



(a) (b)

(c) (d)

Fig. 5. Non-symmetric excitation. In-resonance near field patterns of twin silicon nanowires of the radius a = 200 nm, h = 5 nm and β = 0.5 at λ = 326.16 (a), 328.13 (b), 329.15 (c) and 330.03 nm (d)

Other data on the DR on twin circular metal and dielectric nanowires are in my conference and journal papers [1-6].

III. CONCLUSIONS

A periodically modulated electron beam induces the secondary currents on the nearby obstacles that radiate in the background medium even if the beam does not touch them. As we have shown, a pair of identical dielectric nanowires behaves as a high-Q optical open resonator, which supports supermodes built on the natural modes of each wire, combined together according to the two-fold symmetry of this configuration. The power of DR is resonantly enhanced near each natural supermode wavelength. What is important for applications related to the beam position and velocity monitoring, some of these resonances becomes visible only if the beam trajectory shifts away from the central (i.e. symmetrical) position. Regarding the feasibility of the beam nanosensor, we can remind that today's technologies allow controlled manufacturing of subwavelength optical dielectric microcavities at the scale of dozens of nanometers. Besides, as known, if the dielectric permittivity of a scatterer is constant (no frequency dispersion), then the electromagnetic wave scattering is scalable. As a result, the curves presented in Figs. 3 for the wire with the radius 200 nm and the wavelengths of 320 nm to 340 nm, remain the same for the wire with the radius 2 mm and the wavelengths from 3.2 mm to 3.4 mm.

IV. IMPACT OF MTT-S SCHOLARSHIP AND FUTURE PLANS

Undoubtedly, it is a great honor to be a recipient of the prestigious scholarship from the IEEE MTT Society. This scholarship is actually the first meaningful achievement and recognition in my research career. Therefore it has encouraged me to continue my current research and gave an opportunity to present some results of my work at international conferences held this year. In addition, I hope to attend in 2019 a conference sponsored by MTT-S and get the opportunity to interact with other researchers in the field of microwave theory and techniques. My future career plan is earning the PhD degree in computational electromagnetics.

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