Subwavelength circuitry based on high-index dielectric nanoparticles

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Abstract

We study the subwavelength guiding properties of arrays of high-index dielectric nanoparticles, originating from the long-range coupling of the effective electric and magnetic Mie resonance modes supported by individual nanoparticles. We analyze the dispersion properties of straight coupled-resonator optical waveguides by using coupled-dipole approach, and then verify the validity of the coupled-dipole model by comparing the results with direct numerical simulations and also with microwave experiments. We reveal that a chain of silicon nanoparticles with realistic material losses can guide light for the distances exceeding several tens of micrometres, and it can transmit the energy through sharp bends and defects.

1. Introduction

A new type of optical waveguides, based on the guiding properties of an array of coupled high-Q optical resonators [1]. The most interesting realization of such novel waveguides was proposed in the form of chains of metallic nanoparticles with the ability to support subwavelength localized waves guided due to the excitation of surface plasmon polaritons (SPP) [2, 3, 4]. Very small sizes of plasmonic nanoparticles and ability of bending of such waveguides without any significant reduction of a signal propagation suggest their use as building blocks for photonic integrated circuits [5]. But it was found that mainly by dissipative losses in metal propagation distances of optical signals in plasmonic chains are rather small (of an order of 1 μm), which limits applications of waveguides based on plasmonic nanoparticles.

One of the approaches that can improve the propagation distances of optical signals in chain waveguides is to use dielectric nanoparticles with high refractive index, such as silicon. It was experimentally demonstarted, that silicon spherical subwavelength nanoparticles can support both magnetic dipole (MD) and electric dipole (ED) resonances in optical frequency range [6, 7]. The most important advantages of dielectric particles over plasmonic ones, when it comes to the waveguide applications, is the level of losses, which is in several times lower in silicon than in metals.

In Refs. [8, 9] it was shown numerically that a chain of infinitely long circular GaAs rods with radius 100 nm (below the diffraction limit) and a chain of appropriately arranged dielectric nanospheres with high refractive index allows the energy transfer with a subwavelength transverse confinement, and also that propagating signals can be transported around corners and splitted with Y-type structures. Although the use of dielectric particles imposes a low limit on the particles size, a much higher propagation distances are expected in dielectric chain-waveguides comparing to the plasmonic arrays. Consistent theory based on a dipole approximation, that allows to study the dispersion characteristics of complex dipolar waves in arrays of electric and/or magnetic dipoles was developed in [10, 11]. Here, we employ this theoretical approach to study the dispersion properties of one-dimensional chain of silicon nanoparticles, schematically shown in Fig. 1, which under certain conditions can be modeled as an array of electric and magnetic dipoles. To determine the guiding properties and justify the applicability of the dipole model, we compare theoretical results with direct numerical simulations.

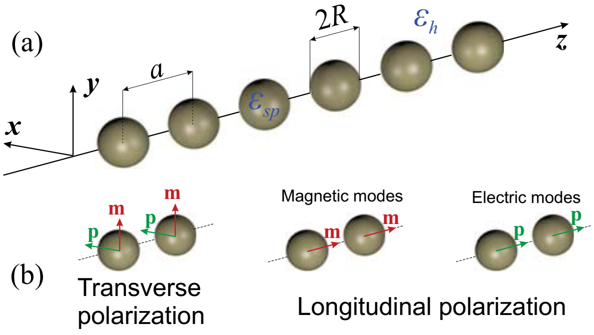

Figure 1: (a) Infinite chain of dielectric (with permittivity ε_{sp}) particles with radius R and period a, located in the host medium with permittivity ε_h. (b) Schematic of the eigenmodes in a chain of nanoparticles.

2. Numerical results and discussion

Here we study the characteristics of guided waves in chains of lossless silicon particles. Real-valued solutions are obtained by solving analytical dispersion equations for the period $a = 140$ nm and are shown in Fig. 2(a). Two

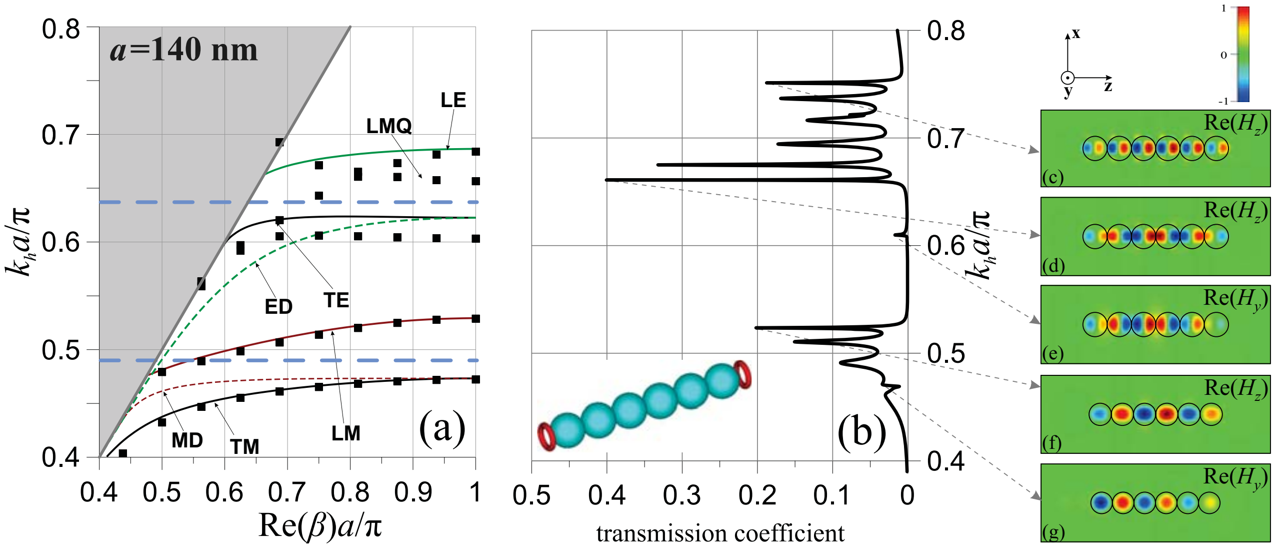

Figure 2: (a) Dispersion diagram of an infinite chain of lossless spherical silicon nanoparticles (TM, TE, LM, LE) and uncoupled chains of electric and magnetic dipoles (MD, ED) for period of 140 nm. Only real solutions of dispersion equations for both transverse and longitudinal polarizations are shown. Eigenmodes, numerically calculated in MPB package, are shown with black squares. Oblique grey line is the light line. Horizontal dashed blue lines indicate the positions of MD and ED resonance frequencies. (b) Numerically calculated transmission spectrum of a chain of 6 silicon spheres with period $a = 140$ nm. (c–g) electric field distributions in the corresponding modes. The operational range of normalized frequenices $k_h a/\pi$ lies within an optical spectral range for the chosen parameters.

black solid curves, marked as TM and TE, are the transversely polarized modes. We also show the dispersion curves for non-interacting chains of magnetic and electric dipoles, i.e. when electric moment vanishes (purely magnetic transverse-polarized modes, marked with MD), and when magnetic moment vanishes (purely electric transversely polarized modes, marked with ED). In contrast to the transversely polarized modes, for the longitudinally polarized modes there is no coupling between magnetic and electric dipoles, so red and green curves, marked with LM and LE, are solutions of the independent dispersion equations in the case of longitudinal polarization.

As one can observe in Fig. 2(a), when the gap between the particles is absent, difference in dispersion curves TM, MD and TE, ED is rather significant, which emphasizes the necessity of consideration of both magnetic and electric responses, especially for the chains of small periods. For larger periods this difference becomes less substantial (not shown here). To determine the conditions under which the dipole approximation model is still valid, in Fig. 2(a) we also compare the results, obtained with the analytical model, and the numerical results, shown with black squares, calculated using the MPB package [12]. Two numerically found guided low-frequency TM and LM modes coincide exactly with the analytical model. Electric transverse TE and longitudinal LE modes are well described by the dipole model, when there exists a large enough gap between the spheres, but when the gap vanishes, the dipole model exhibits a small inaccuracy near the ED resonance. Numerical calculations also indicate the generation of higher–order multipole modes, absent in the dipole model. Magnetic quadrupole (MQ) resonance frequency of a silicon sphere lies higher than ED resonance frequency, but the corresponding longitudinal magnetic quadrupole (LMQ) band broadens, when the period of chain decreases, shifting partially to lower frequencies, thus, making the dipole approximation incomplete near the ED resonance frequency for very small periods. Other multipole modes remain at higher frequencies, and we do not show them in Fig. 2(a). So unlike the plasmonic chain-waveguides, eigenmodes of a silicon chain-waveguide can be very accurately described within a dipole approximation in a wide range of parameters.

To study the realistic case of chains of a finite extent and to check a possibility of exciting the numerically found eigenmodes, we simulated in CST Microwave studio transmission of optical signal generated by a magnetic loop probe through a chain of six silicon spheres with 140 nm period [Figs. 2(b)]. We clearly observe a transmission band around $k_h a/\pi = 0.5$ formed by excited TM and LM modes. Transmission band around $k_h a/\pi = 0.7$ is formed by multipole modes. The most high-frequency peak corresponds to the LMQ mode with $\beta = 0$. This mode crosses the light line (i.e. it is a radiating leaky wave), and therefore it is not shown in Fig. 2(a), where only unattenuated modes are present. Numerically found frequency for $\beta = 0$ is $k_h a/\pi \approx 0.76$, which coincide with the value in transmission spectrum at the upper edge of the longitudinal magnetic quadrupole band [Fig. 2(c)]. One can also see a transmission peak at $k_h a/\pi \approx 0.61$ [Figs. 2(e)] corresponding to the TE mode, which is also excited due to the inhomogeneity of current in the probes.

The use of analytical dipole model allows us to estimate such important characteristic of a waveguide as a balance between the propagation distance $z_0 = 1/[2\mathrm{Im}(\beta)]$ and the field localization in the transverse direction. By adding the material losses ($\mathrm{Im}(\varepsilon_{sp}) = 0.1$, which corresponds to the wavelength $\lambda \approx 700$ nm) in the model, we find that propagation distances for transversely polarized modes can reach values of about 10 μm. TM modes are well described within a dipole model, so such estimates can be considered as pretty accurate. Besides, in the spectral range 700–1000 nm losses in silicon are several tens of times less, and therefore the propagation distances can reach tens and even hundreds micrometers, while the radius of the field localization would be considerably less than the operating wavelength. Comparison to the nano-waveguides, based on plasmonic particles, indicates the apparent advantage of the waveguides composed of dielectric nanoparticles, so that the propagation lengths more than 10 μm can be achieved with silicon nanospheres even at frequencies where losses are rather strong for dielectric material.

3. Conclusions

We have analyzed the dispersion properties of chains of silicon nanoparticles. We have shown that such nanoparticle chains create subwavelength waveguides that support MD, ED and MQ guided modes with reasonable propagation distances and subwavelength localization. A comparison with numerical simulations indicates that the coupled-dipole model describes very accurately MD modes, and remains valid for ED modes in the case of large spacing. For small lattice spacings, MQ mode shifts to lower frequencies, and the dipole model gives inaccurate predictions at the frequencies near the ED resonance. More accurate description requires to take into account also the MQ moment.

We emphasize that for the analysis of the guided modes in a chain of silicon particles it is necessary taking into account both magnetic and electric moments. Interaction between the EDs and MDs affects strongly the dispersion characteristics of leaky waves and also guided waves, when the lattice spacing becomes small.

Our analytical and numerical results, were also verified by microwave experiments, which indicate the advantages of chains of silicon nanoparticles over plasmonic arrays and confirm a promising perspective of using them as waveguides with the subwavelength guiding in optical integrated circuits.

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