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Collective states with high quality factors in chains of dielectric resonators

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Abstract. Coupled dielectric subwavelength resonators supporting collective states with high quality factors are of interest due to potential in the enhancement of the light-matter interaction at the nanoscale and high versatility and tunability of such structures. Recently, it was theoretically shown that coupling between two or more collective modes via radiation continuum that can occur under variation of the parameters of such structures could significantly boost the quality factor of one of the eigenmodes. In this work, we have studied such effect numerically and experimentally for a chain of ceramic cylinders operating in the microwave spectral range. We have investigated how the present channels of losses, namely material losses, and additional scattering due to variation in geometrical and materials parameters, influence the considered effect. We have developed a feasible design that allows for observation of mode interaction. Experimental measurements of the spectral response of the proposed structures confirmed the main predicted results.

Keywords: dielectric resonators, band edge states, interaction of resonances, nanophotonics, microwave prototyping

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Материалы конференции
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Коллективные состояния с высокой добротностью в цепочках диэлектрических резонаторов

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Аннотация. Цепочки связанных диэлектрических субволновых резонаторов, поддерживающие коллективные резонансные состояния с большими добротностями, представляют интерес благодаря усилению взаимодействия света с веществом, а также возможности по настройке параметров таких структур. Недавно было теоретически показано, что взаимодействие между двумя или более коллективными модами через излучение континуума, которое может возникать при изменении параметров таких структур, значительно повышает добротность одной из мод. В данной работе мы исследовали такой эффект численно и экспериментально для цепочки керамических цилиндров, функционирующих в микроволновом диапазоне спектра. Экспериментальные измерения спектрального отклика разработанных структур позволили пронаблюдать взаимодействием мод и подтвердили основные теоретически предсказанные результаты.

Ключевые слова: диэлектрические резонаторы, коллективные моды, взаимодействие резонансов, нанофотоника, прототипирование в микроволновом диапазоне спектра

Финансирование: Численное моделирование было выполнено при поддержке гранта РФФИ № 20-52-12062. Экспериментальные измерения были выполнены при поддержке гранта РНФ № 22-72-10047.

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Introduction

All-dielectric optical resonant structures supporting resonances with high quality factors and allowing to localize electromagnetic fields in a small volume are of both fundamental and applied interest due to significant increase of light-matter interaction strength. One type of such structures are ensembles of coupled dielectric subwavelength resonators [1, 2]. Due to the interference of radiation from individual elements, such structures support collective resonant oscillations, characterized by suppressed radiative losses and consequently high quality factors. It has been experimentally shown that such systems allow to enhance the nonlinear response of the material of which they are made [2], to enhance the photoluminescence intensity of the quantum dots integrated into them [3], to achieve regime of laser generation [4], and act as a platform for on chip sensing [5].

Besides destructive interference between radiation from individual particles in an ensemble, coupling between two or more modes via radiation continuum can occur under variation of the parameters of such structures. In this case the quality factor of one of the eigenmodes can be substantially increased. For example, this can be achieved by precision control of the gap between individual resonators in the chain [6]. This mechanism can be explained by a change of the dispersion curve of the corresponding infinite chain of particles, namely, by the appearance of an inflection point near the edge of the Brillouin zone, which leads to the destructive mode interference of the corresponding finite chain. However, this effect has been predicted only theoretically and not investigated experimentally.

In this work, we have investigated the possibility of experimental realization of the chain of dielectric resonators that support eigenmodes with high quality factors that appear due to interaction of two collective modes of the chain via radiation continuum. We have analyzed what kind of geometrical and material parameters allow to achieve such regime. We have investigated how the present channels of losses, namely material losses, and additional scattering due to variation in geometrical and materials parameters, affect the considered effect. Based on the performed analysis we have developed several feasible designs of the chains of ceramic resonators, that support high-Q modes in microwave spectral range. We have performed experimental measurements of the spectral response of the proposed structures, which confirmed the main predicted results.

Materials and Methods

In order to analyze the spectral response of an individual block of a chain of dielectric resonator we have perform multipole decomposition using the method proposed by [7], which allows one to consider resonators of arbitrary shape. In this work, we employ subwavelength ceramic resonators with high permittivity ($\varepsilon \approx 44.8$), which allows us to use fundamental dipole resonances supported by these resonators.

Analysis of the dispersion properties of the infinite chain and eigenmodes of the finite chain is performed via full-wave numerical simulations. In the case of infinite chain, we are interested in the waveguide modes supported by the chain, which are characterized by real-valued eigenfrequencies (in case of zero material losses). In contrast, in finite chain the eigenmodes always lose energy through radiative losses, and therefore, eigenfrequencies are complex. The ratio of real and imaginary part determines the quality factor, which is the main characteristic in this study.

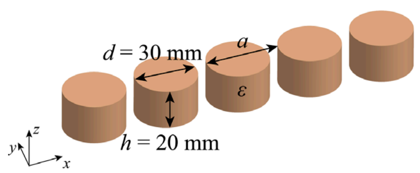
For experimental verification, scattering parameters (*S*-parameters) of a finite chain were measured. To control the gap between the individual cylinders in the chain, we have fabricated a sample holder made from Penoplex foam material ($\varepsilon \approx 1$) by a computer numerical control machine drilling. The holder consisted of a set of circular wells with different distances between the centers of the wells *a*, ranging from 33 mm to 45 mm in 0.5 mm increments. Excitation of modes in chain was done via near-field coupling of the source to the chain. The antennas were connected to the corresponding ports on the Rohde & Schwarz vector network analyzer. Next, the S_{21} parameter was measured for different values of the distance *a*.

Deviations in the dielectric permittivity values of individual cylinders lead to changes in the resonant frequencies of the respective cylinders. In turn, for the case of the finite chain, this affects both the maximum possible values of the quality factor of the collective mode and the corresponding optimal values of the distance *a*. In order to reduce the influence of disorder in the dielectric permittivity of the individual cylinders, scattering parameters were measured for all cylinders, allowing 5 cylinders with the closest resonance frequencies to be selected.

Results and Discussion

We have developed a potential design based on the ceramic cylinders with the following parameters: height of the cylinders $h = 20$ mm, and diameter of the cylinders $d = 30$ mm. The period of the chain was varied in the range $a \approx 30–45$ mm. As it will be shown further the resonant wavelength of the considered mode will be $\lambda_0 \approx 200$ mm, which makes the considered values of period approximately 5–6 times less. The relative permittivity of the ceramic material was $\varepsilon \approx 44.8$. The material losses in ceramics were described by the dissipation factor (or loss tangent) $\tan\delta = \mathrm{Im}(\varepsilon) / \mathrm{Re}(\varepsilon)$, taking characteristic values in the range from 1×10^{-5} to 1×10^{-4}. A schematic representation of the cylinder chain is shown in Fig. 1, *a*.

At the first step, we have analyzed the response of the individual cylinder. Multipole decomposition performed for a single cylinder has shown that at least first few resonances, which are well separated in frequency, are characterized each by a single dominant multipole contribution. The example of the multipole decomposition performed for a spectral dependence of a scattering cross section of a cylinder excited by a plane wave incident along the diameter of the cylinder with magnetic field polarized along the cylinders axis is shown in Fig. 1, *b*. Given the negligible response of all multipole terms except for one at each of the resonances, we expect the modes of the chain of the cylinders to be formed by coupled multipoles of a single type.



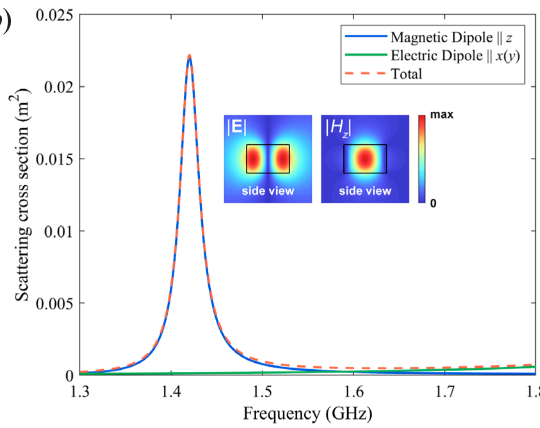


Fig. 1. Schematic of the chain of ceramic cylinders studied in this work (*a*). Multipole decomposition performed for a single cylinder (*b*). The inset shows the distribution of the total electric field and the absolute value of the out-of-plane component of the magnetic field corresponding to the magnetic dipole resonance

At the second step, we have performed numerical calculations of the dispersion curves of the infinite chain, in order to find the range of values of the chain period, in which they exhibit non-monotonic behaviour. The dispersion diagram for an infinite chain for a period a = 32 mm is shown in Fig. 2, *a*. The black dashed line is the light line. We observe that the chain supports a lot of waveguide modes of different types. At least first three modes are well separated spectrally below the light line. This is achieved due to rather large quality factor of the resonances in a single cylinder and rather strong coupling between the cylinders in the chain. Such behaviour helps us to distinguish the modes of different type in the corresponding finite chains in experiment. The variation of the period revealed that few of these modes can have non-monotonic character. We have focused on the fundamental mode that is formed due to coupling magnetic dipole resonances in individual cylinders. Dispersion diagrams for this mode, calculated for different values of period a, are shown in Fig. 2, *b*. The inset of Fig. 2, *b* shows the distribution of the absolute value of the out-of-plane magnetic field component and the absolute value of the electric field in the lateral cross-section of the cylinder. As one can see from Fig. 2, *b*, when the period of the chain is greater than a_{cr}, the dispersion curve of the first resonant mode is monotonic. Then, as the period of the chain decreases, the dispersion curve changes its behaviuor, becoming non-monotonic, starting from some value of period $a < a_{cr}$.

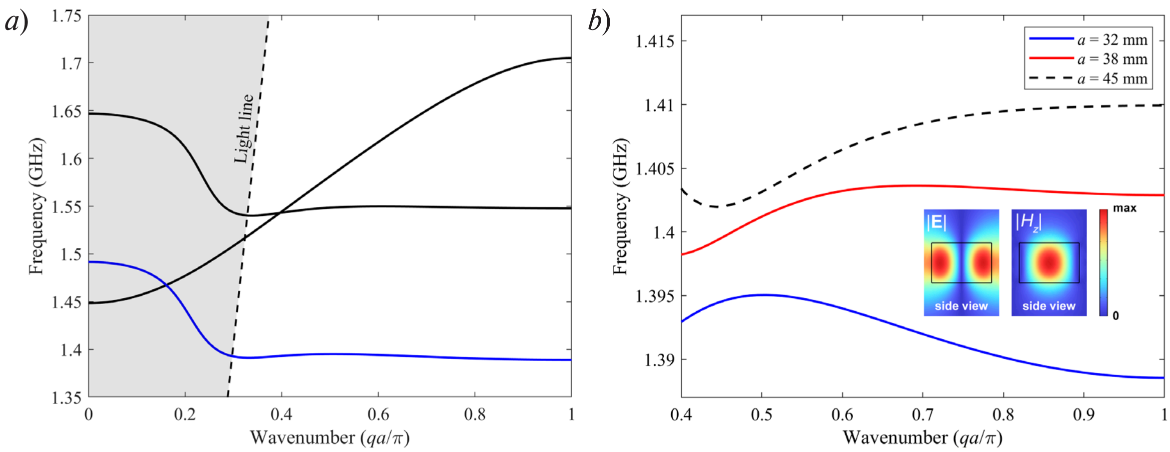


Fig. 2. Dispersion diagram for an infinite chain of ceramic cylinders for the period a = 32 mm (*a*). First dispersion branch of the chain of ceramic cylinders for different values of the period a (*b*). The inset shows the distribution of the total electric field and the absolute value of the out-of-plane component of the magnetic field at the edge of the Brillouin zone

After estimation of the parameters of the chain that allow for observation of the interacting collective modes, we have performed the calculations of the quality factor of the finite chain eigenmodes. For finite chains consisted of N resonators one expects to observe Fabry—Perot resonances at the frequencies related to the Bloch wavenumbers q through the dispersion of the infinite chain as follows: $qa / \pi = 1 - \xi / (N + 1)$, where ξ is the number of resonance [8]. Therefore, for the period a = 38 mm, the inflection point of the dispersion curve corresponds to $qa / \pi \approx 0.7$, which allows us to expect the appearance of the high-Q mode in a finite chain of 5—6 resonators for the corresponding second resonance.

In order to find the parameters at which the formation of high-Q collective mode is observed, we have calculated the dependence of the total Q-factor on the period of the chain a in the range 30—45 mm near the value 38 mm expected from the analysis of the infinite chain. The results for a chain consisting of 5 cylinders are shown in Fig. 3, *a*. One can observe that for a certain value of the period the radiation losses become suppresses and the Q-factor reaches the maximal value, which according to the theory [6] indicates the interference between two collective states. Calculations made for $\tan\delta = 1 \times 10^{-4}$ show that such level of losses still allows to observe the studied effect.

To confirm the predicted results experimentally we have performed the measurements of the spectral response of the chain of 5 cylinders according to the method described above. The excitation of the chain was performed by the magnetic loop antenna placed above the central cylinder, which allowed us to excite only modes of specific parity. Since other two modes of this parity were well separated in frequency, in experiment we have seen a dominant Lorentzian-type response, which allowed us to easily extract a quality factor of this mode. The results of the measured Q-factors for different values of the period are shown in Fig. 3, *b*. The main qualitative result, namely the presence of the maximum in $Q(a)$ dependence was confirmed. The discrepancy between the optimal value of the period and the maximal value of Q-factor can be explained by slight difference between the spectral response of the cylinders as well as slight deviations of the real values of periods from the optimal ones.

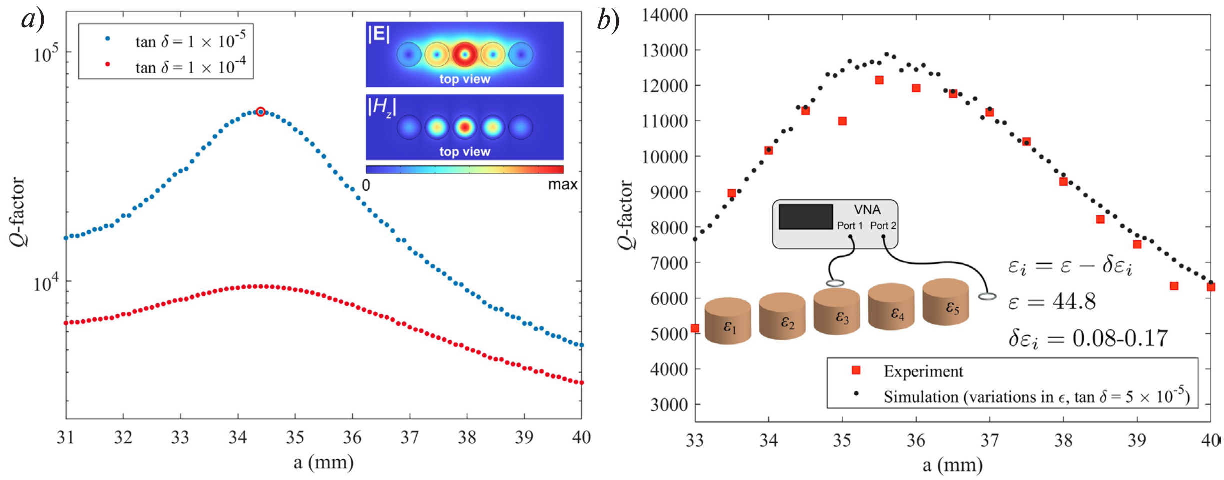


Fig. 3. Dependence of the Q-factor of the mode with the highest Q of the chain with 5 cylinders on the period of the chain. The inset shows the distribution of the total electric field and the absolute value of the out-of-plane component of the magnetic field in the chain for the parameters at which the Q-factor takes the highest value (the corresponding point is marked with a red circle) (*a*). Dependence of the Q-factor of the chain of 5 cylinders on the period extracted from the experimental data and the calculated data with introduced deviations in dielectric permittivity of individual cylinders, the inset shows the schematic of the experimental setup (*b*)

Conclusion

In conclusion, we have developed the design of the chain of ceramic cylinders that support eigenmodes with high quality factors, that is enhanced due to interaction of two collective modes of the chain via radiation continuum. We have experimentally shown that the quality factor of one of the modes of the chain exhibits a maximum in the dependence on the period of the chain, indicating the presence of interacting resonances. We have revealed that even slight change of the parameters of the chain significantly reduce the strength of the considered effect. We believe that the obtained results will allow for the design of high-Q dielectric resonators based on the collective modes in compact dielectric structures.

Acknowledgments

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