

Mesotronics: Some New, Unusual Optical Effects

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Abstract: The recently emerged field of Mesotronics provides novel opportunities for subwavelength magnetic and electric field localization and giant enhancement by mesoscale dielectric particles and structures from low-index to high-index materials, supported by novel optical phenomena. In this case, two regions: non-resonant and resonant, can be distinguished. In this short review, which is a direct continuation of our recently published study, we continue to present the authors' point of view on some new optical effects in dielectric mesotronics. Among them are anomalous apodization effect in phase mesoscale gratings, new effects on high order Fano-resonances and extreme effects in field localization, mesoscale particle-based super-resolution and high-speed communications, photonic hook-based high-contrast subwavelength imaging, and reverse optical energy flow in a perforated resonant spherical particle.

Keywords: mesotronics; extreme fields; subwavelength imaging; optical energy backflow

1. Introduction

The term "photon" derives from the Greek (fotov)", which means "light", so the term "nanophotonic" means light at the nanoscale and is concerned with the interaction of light with nanoscale structures [1,2]. As is known, the part of photonics called plasmonics [3] is based on dielectric structures placed on a metal surface or metal components using plasmons, which is usually directly related to electric dipole resonances. It is important that the materials have a permittivity with real parts of the opposite sign [4]. In metals, the refractive index is negative, and a metal behaves like a mirror: a wave penetrates into it by the skin layer value. Therefore, plasmonics is usually characterized by an electric field localization near the metal and dielectric surfaces. Furthermore, it is possible to localize light in a volume that is less than the diffraction limit of classical free-space optics [3–6]. However, a metal heats up and large Ohmic losses occur, since it has free electrons and dissipative losses are high, and that limits their application. For example, the plasmon waves propagation distance is of nanoscale dimensions [1].

The concepts based on fully dielectric resonant nanoparticles allow overcoming the limitations caused by dissipative losses [7–9]. In dielectric materials, the polarization current is much greater than the conduction current and increases with the increasing dielectric constant of a material. Dielectric structures that support geometric (or Mie) resonances are able to localize light, although the size of Mie resonators is larger than that of plasmonics. The existence of Mie resonances in dielectrics leads to electric and magnetic modes. The latter, due to constructive interference, give a magnetic response of the structure. Thus, due to such resonances, excitation of magnetic properties in non-magnetic materials is possible. For the spherical particles, these resonances can be described by the exact Mie theory [10]. The optical properties of spheres in this theory are characterized by the size parameter $q = 2\pi R/\lambda$ (where λ is the radiation wavelength, R is the radius of the spherical particle) and refractive index contrast [11].



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2. Mie Resonance-Driven Dielectric Nanophotonics

Magnetic and electric Mie resonances of different orders occur when the light wavelength inside the particle material becomes comparable to its size [11,12], because electromagnetic waves cannot last long in a dielectric cavity of a smaller size [13]. The number of excited magnetic and electric modes and their order depend on q and the particle refractive index n . In addition, as the size parameter q decreases, higher-order modes are excited. In particular, this explains the interest in dielectric particles with a high refractive index. This field of nanophotonics was called “meta-optics” [14–16] by Y. Kivshar (*Meta* from the Greek *μετά* means “beyond”) because dielectric materials in optics are usually non-magnetic.

Dielectric high-index particles with $q \sim 1$ support magnetic and electric dipoles, magnetic and electric quadrupoles, etc. The existence of magnetic and electric modes in such materials allows their constructive interference. Apparently, attention was first drawn to this in the study [17] by B.S. Luk'yanchuk et al., where the term “magnetic light” was introduced. Similarly, in meta-optics, the subwavelength dielectric structures become driven by the interference of multipolar modes. Overlapping magnetic and electric Mie resonances also make it possible to design media with a negative refractive index [18] and low losses [19]. Moreover, for example, the circular displacement current in one plane of dielectric spherical particle is indicative of a magnetic dipole moment [20].

The so-called *Mie-tronics*, or *Mie-resonant meta-photonics* [21,22], studies the scattering for the *high-index* particle size parameter q less than 1 and uses a single particle as a building block for metamaterials [23,24]. It could be noted that combining the fields of plasmonic optics and metamaterials allowed the development of the concept of “meta-tronics” [25,26] (introduced by N. Engheta)—metamaterial-based nanoelectronics—in which optical waves can be manipulated by collections of nanostructures [27–29].

3. Dielectric Mesotronics

At the same time, dielectric particles with the diameter greater than or even equal to the wavelength (size parameter q of the order of 10 [30–32]) occupy a little-studied niche between nanoparticles ($q < 1$) and particles ($q \sim 100$) for which geometric optics is valid [30,32]. In other words, mesotronics is devoted to mesoscale single particles and/or structures with building blocks which are large enough to support internal resonances (such as Mie resonance or whispering gallery modes in dielectric spheres), but at the same time are small enough so that geometrical optics cannot be applied for studying their optical resonant and non-resonant properties (typically $q \sim 10$). In such structures, a significantly larger number of interfering modes is observed than in subwave structures, and one can expect the appearance of new interesting physical and practically important effects. Although the interest in such particles arose more than a century ago when explaining the unusual optical effects of light scattering by suspensions of finely dispersed sulfur [33] or water droplets [34], note that even in ancient times, they knew that a garden should be watered at a certain time, since water droplets have focused properties [30,35,36].

At the end of the 1960s Professor Vladilen F. Minin and his team found [36] that anomalously large values of the backscattering cross section Q_{BS} [10] are reached for a sphere with $q > 20$ with an absorption coefficient $k < 0.001$ and a refractive index in the range of $1.8 < n < 2$. The width of the Q_{BS} function narrows near $n = 1.91$ as the size parameter q increases (Figure 1).

This field of dielectric photonics that we call *Mesotronics* [31,36,37] is relatively new and various novel physical phenomena have only recently been revealed. Mesotronics is dielectric photonics driven by optical effects in mesoscale particles, both in non-resonant and resonant modes, including resonantly trapped light inside mesoscale building blocks. Mesoscale dielectric particles are larger in size than plasmonics and Mie-tronics, but they have both magnetic and electric responses in low-index and in moderate and high refractive index particles. Moreover, usually plasmonic structures have a relatively small Q factor of about 10. The Q factor dielectric Mie-resonant particle array can be up to 10^5 . A single mesoscale sphere supporting a high-order Fano resonance has a Q factor of

about 10^8 . Among non-resonant effects, we have previously briefly reviewed the following ones: localized structured fields in the form of photonic nanojets, hooks and loops, plasmonic jets and hooks, magnetic jet, specular-reflection photonic nanojet, terajets and acoustic jet, overcoming the diffraction limit and image quality improvement, anomalous apodization effect in mesoscale single particles, nano-vortices, optical hearts, waveguiding structures, etc. [30–32,36,37]. Among the resonance effects, we note: anapole, high-order Fano resonances in dielectric spheres and giant magnetic field generation in mesoscale particles [31,32,36,37].

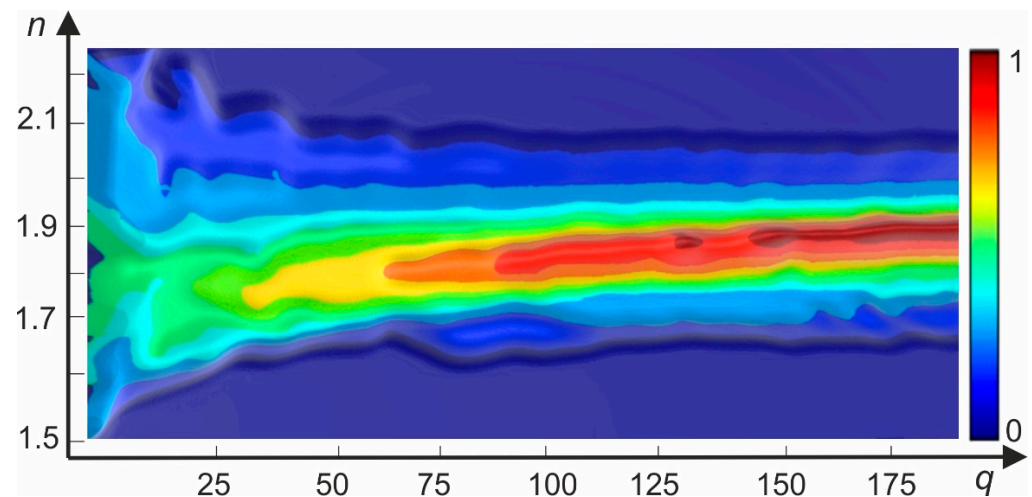


Figure 1. QBS function for polydisperse (10% for particle diameter) mesoscale dielectric spheres vs. Mie size parameter q . Adopted from [36].

Below, in this short paper, we continue [31] to consider some of the interesting physical concepts and novel optical effects in the framework of mesotronics.

4. The Anomalous Apodization Effect in Mesoscale Gratings

The idea that the performance of simple mesoscale particle-lenses can be enhanced by the anomalous apodization effect without losses of the field enhancement is a new paradigm for the optical community, with wide implications. This effect was first discovered by Minin and Minin [31] for mesoscale single particles of various nonspherical shapes [38,39]. The effect was that the mask introduction in the irradiated particle surface led to a smaller number of optical vortices near the particle shadow-side surface and, thus, allowed reducing the photonic jet beam waist at its intensity increase. This effect was extended to mesoscale phase diffraction gratings. It could be noted that “Mesotronics” studies both an isolated particle and arrays of mesoscale particles, where a building block (unit cell) is comparable or more than the wavelength. In contrast to metasurfaces that consist of subwavelength unit cells and control the wave parameters within a distance much less than the wavelength. Apodization-assisted subdiffraction near-field localization in a two-dimensional phase diffraction grating is caused by a Fano resonance, which occurs in a mesoscale structure due to the effective interaction between the Fabry–Perot interference and the structural Mie resonance [40]. The hybridization of Fabry–Perot and Mie-like modes at the crossing point can lead to the appearance of a quasi-bound state in continuum in mesoscale diffraction gratings with an apodization mask due to the suppression of leakage outside. As it was shown for the first time in [40], such a method provides an important and useful mechanism to suppress radiation and obtain the localized energy with a back flow with an optimized vortex structure inside the phase step of diffraction grating (Figure 2).

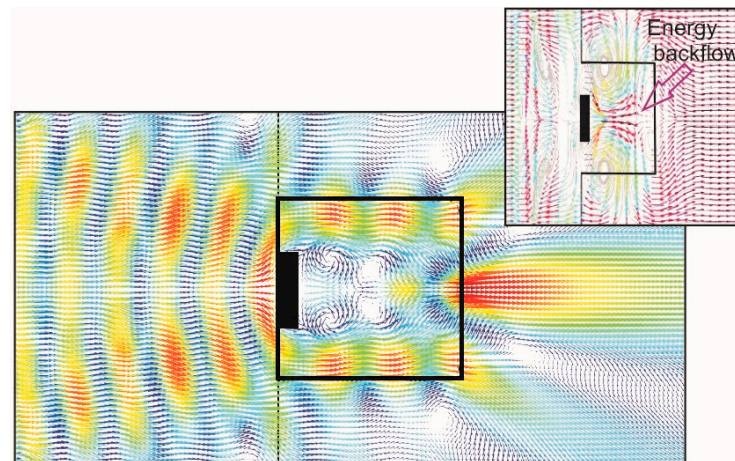


Figure 2. Poynting vector distribution and optical vortices in the phase step of mesoscale apodized diffraction grating. In the inset is the vortex structure of the optical flow for the optimized mask which blocks the photonic jet formation.

Figure 2 shows two different functioning modes of the structure under consideration. The main figure shows the effect of the combined action by a Fano resonance and the structural Mie resonance, which leads to a stronger field localization (photonic jet) and, accordingly, to a decrease in the beam diameter. In the inset, there is another mode when partial apodization leads to the appearance of a vortex near the shadow part of the grating and the appearance of energy backflows, i.e., the “stop filter” regime.

In the application of the above-mentioned effect to the Talbot effect, one can allow increasing the spatial resolution up to the subdiffraction ($\sim \lambda/4$), providing the highest optical contrast (~ 22 dB) [41]. Similar approaches were considered later by other researchers [42] but without reference to earlier studies [41].

5. High Order Fano-Resonances and Extreme Effects in Field Localization

In 2019, we showed that dielectric weak dissipative mesoscale spherical particles could support high-order Fano resonance modes [43,44]. These internal Fano resonances for specific size parameter values yield field-intensity enhancement factors of about 10^4 – 10^8 , which can be directly obtained from Mie theory [31,36,37,43,44]. In particular, these “super-resonances” provide magnetic photonic jets [31,32,37,43] with giant magnetic and electric fields intensities.

Bearing in mind that vacuum as a surrounding medium is an unachievable idealization never realized in actual physical systems, the investigation of influence effects of surrounding medium in this problem raises it to a much higher level. Our contributions [45,46] were one of the first attempts to answer these questions in the case of high order Mie resonance in the presence of surrounding medium. It was shown that the spectral position of the resonance peaks can be changed in a controllable way by changing the size parameter and the relative refractive index of the sphere material, as well as the environmental conditions. For example, for a sphere located in water [46] (the resonant mode $l = 55$), a change in the medium efficient refractive index by 2×10^{-6} (that is equivalent, for example, to a change in water temperature by approximately $\Delta T = 0.01$ °C) leads to a twofold drop in the field intensity for the same size parameter.

Note that of particular interest for application are dielectric structures, which can present tunable properties, and which can be dynamically controlled by external stimuli. In the case of consideration as an external influence, a change in the refractive index of the surrounding medium can be, for example, under the action of pressure, temperature, or impurities. A small change in the refractive index of medium will lead to a violation of the super-resonance condition and a change in the intensity and shape of the field localization from hot spots to a photonic jet.

It is also interesting to note the following. A common answer to the question “How can we maximize the radiation confinement in a dielectric particle?” is to “make it so as to minimize the dissipative constant of the particle material”. However, surprisingly enough, it turns out that the correct answer is exactly the opposite: a small energy dissipation in the sphere material can also contribute (rather than worsen) to the subdiffraction field confinement [44], i.e., its dissipative constant must be low, but not equal to zero. For a spherical mesoscale particle made of BK7 borosilicate glass (which has its complex refractive index of the particle material $n = n_s + ik$, where $n_s = 1.5195$, $k = 7 \times 10^{-9}$ [47]), it was demonstrated for the first time that the presence of a small dissipation in a particle material can lead not to a decrease but to an increase in the intensity of the generated fields [48]. The latter is related to the unusual behavior of the Mie scattering coefficients of the particle internal field under super-resonance conditions.

Additionally, the question of whether there can be a high-order Fano resonance [49] in spheres with a low refractive index has recently been considered. Taking into account the low refractive index contrast, such nanoparticles are generally unsuitable for the magnetic response induction [50,51] due to poor light confinement. So confining and light localization in low refractive index particles is challenging, owing to the light leakage through coupling to narrow modes in the surrounding medium [52]. However, the use of mesoscale spheres with a low index material makes it possible to realize high-order Fano resonances *ab initio*.

Although Mie scattering on large water drops has long been studied [53,54], it was for the first time shown that for a dielectric sphere with a refractive index about $n = 1.33$ (water droplet) and size parameter of $q = 70.60$ it is possible to excite Fano resonances of an extremely high ($l \sim 90$) order with a significant increase (up to 10^7) in the magnetic and electric fields intensities [55]. The quality factor of water-based spherical particle is about $Q = 6 \times 10^8$ with a resonance line width of about $\Delta\lambda = 8 \times 10^{-6}$ nm at a resonant wavelength $\lambda = 533.939$ nm [55]. In this regard, we note the following. It is theoretically possible to increase the quality factor Q of the resonance by increasing, for example, the size parameter accuracy. However, with such a quality factor, the resonance line width will be of an order of about $\sim \lambda/Q$, which is very difficult to measure in optics. In this case, any inhomogeneities of this order will shift and destroy the resonance [45]. Therefore, it is hardly justified and expedient to consider super-resonance effects with a size parameter q , which has an accuracy better than 10^{-5} .

In our opinion, further prospects for studying the super-resonance effect related to hollow or concentric multilayer spherical particle, where we can control the position of various resonances. Apparently, the super-resonance effects in this case can obtain new properties. Such high-order Fano resonances are kinds of magnetic “nanostructured generators” with giant localized fields, including magnetic nanojets with giant magnetic fields, which are attractive for many practical applications, including next-generation mesotronics [31,36,37]. The instant giant localized magnetic near fields are comparable to those in neutron stars, introducing a new method for the creation of extremely high magnetic fields on the mesoscale in laboratory conditions. Additionally, these findings may provide a novel path for the real application of mesoscale all-dielectric photonics.

6. Mesoscale Particle-Based Super-Resolution and High-Speed Communications

The optical system resolution is generally limited by the diffraction limit described by the well-known Abbe and Rayleigh criteria [56]. High-order Fano resonances are accompanied by the formation of regions with high local wave vector values [31,32,36,43,44]. This allows one to overcome the diffraction limit, for example, by using a low-loss dielectric sphere [30,57–67]. Under the conditions of high-order Fano resonance, the characteristic size of hot spots near the sphere poles [57,66] is much smaller than the diffraction limit. We show in [43,44,55] that it is possible to generate deep subwavelength magnetic and electric field localization (hot spots) with the size of about $\lambda/5$, both for magnetic and electric fields and extremely high enhancement factors (which is comparable to plasmonic structures [68]) of the order of 10^7 – 10^8 in the optical range.

Importantly, today there are three main different types of particle-based super-resolution imaging: diffractive conical lens [56], mesoscale particle-based (either cubic or spherical shape) lens and metamaterial solid-immersion lens, all of them have different types of super-resolution imaging physics. In this regard, we note that a metamaterial solid immersion lens based on a single particle or a cluster of mesoscale particles, which convert evanescent waves to propagating ones [69], behaves like an effective medium and does not demonstrate the super-resolution in the far field [70].

The study of the concept of terajets [71–75] in the non-resonant mode, based on particles with an arbitrary 3D shape, has attracted considerable research interest regarding imaging application because a terajet has more symmetric hotspots compared to a sphere [75]. Note that obtaining super-resolution in the terahertz range, despite the scalability of the Maxwell equations, is a more difficult task than in optics. The main reason for this is much greater absorption (by 3–4 orders of magnitude) in the material than that in the optics [76–78]. It was shown for the first time [79] that the mesoscale dielectric particle allows increasing the resolution of the THz imaging system of arbitrary types [79–84] by simply placing it at the focused imaging points. In this case, the obtained subwavelength resolution [79] was equivalent to the resolution of the system at the double frequency. Improving spatial resolution without increasing the frequency of electromagnetic waves is a far-reaching result because increasing the THz frequency leads to an increase in the absorption of materials and a decrease in the terahertz power [79].

The terajet effect—for a cubic mesoscale particle—may be applied as a far-field antenna for the promising 6G networks and indoor communications [85]. The short-range THz wireless transmission using a high-gain and wavelength scaled dimension ($1.36\lambda \times 1.36\lambda \times 1.79\lambda$) PTFE cuboid antenna in the 300 GHz band [86–89] was demonstrated for the first time. The data rate with the amplitude-shift keying of 17.5 Gbit/s was reached (Figure 3). The developed antenna has minimal dimensions integrated into various devices, including a mobile phone, with a sufficient gain compared to other known solutions [90–93].

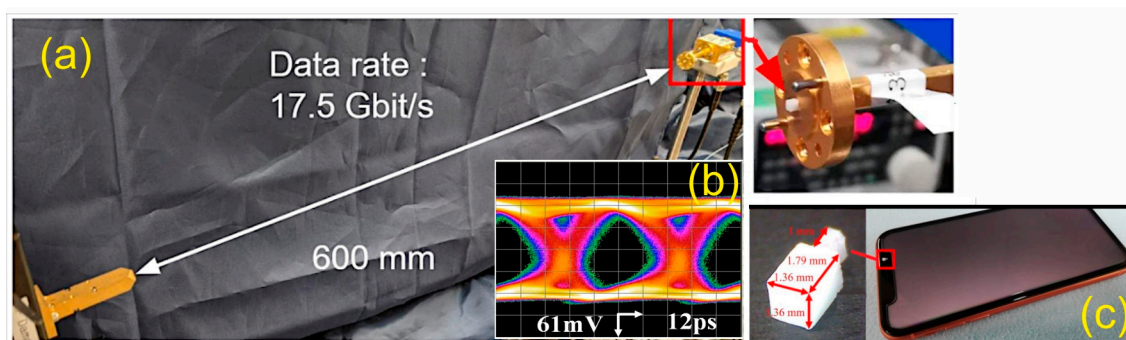


Figure 3. (a) Scheme of the experiment, (b) eye diagram: when the bit-error-rate was the smallest, (c) concept of antenna integrated into a mobile phone. Adapted from [86–89].

7. Photonic Hook Based High-Contrast Subwavelength Imaging

Symmetry violations in structured subwavelength beams such as photonic hook [75] (PH) provide unique opportunities for photonics and applications. The key role of broken symmetry in this case consists of controlling the near-field subwavelength localized curved light beams and their widespread applications for photonics technologies, including auxiliary optomechanical structures. Based on this research, we extended our study to develop a new (to the best of our knowledge) method [94] of photonic hook-based near-field oblique illumination microscopy with super contrast subwavelength imaging. It was experimentally demonstrated [31,95] for the first time that the Janus particle [96–98] provides oblique illumination [99–101] of imaging objects by localized structured curved beams, which leads to a considerable improvement in the near-field imaging contrast without the use of immersion medium (Figure 4). One can see that the oblique illumination (illumination by PH) results in the diffracted order of +1 on the particle, which finally allows increasing

the image contrast. In the case of the axial formation of the classical PNJ, diffracted orders of -1 and $+1$ are beyond the particle boundaries. We believe that these research activities can provide new trends and the basis for a new direction in the development of simpler and more powerful super-resolution high quality imaging systems that could revolutionize optical-type microscopy based on mesoscale particle-lenses.

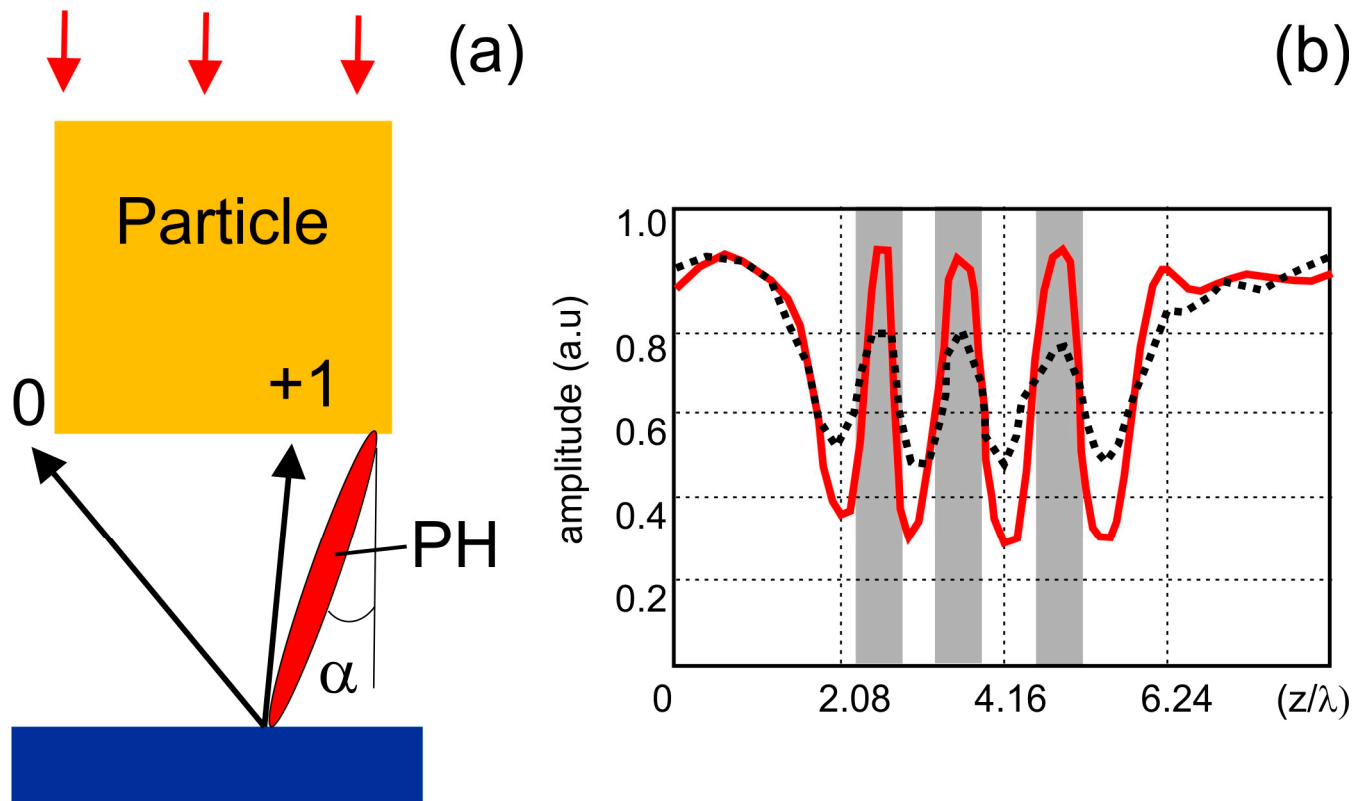


Figure 4. Schematic view of the oblique illumination by a photonic hook (a) and the imaging contrast enhancement of periodic metallic grating (shown in gray) (b) by the illumination of PBJ (black) and PH (red). Adapted from [95].

8. Reverse Optical Energy Flow in a Perforated Spherical Particle

Earlier [31,102,103], we briefly considered some new optical effects in nanostructured mesoscale particles in the nonresonant mode, including the complex flow of optical energy inside the particle [104]. Recently, a new optical effect—the formation of a reverse flow of optical energy directed towards the incidence vector of the initial wave under resonance conditions in a perforated spherical particle at the shadow and illuminated sides—has been discovered and studied [105]. For the first time, a multiple enhancement of the optical energy backflow intensity in the air-filled nanohole in a dielectric mesoscale sphere at resonance conditions was revealed. It could be noted that a reverse optical energy flow plays a key role in the formation of localized superoscillatory fields [106–108]. In the case under consideration, the organization of a controlled reverse energy flow is possible without the use of complex structured illuminating beams such as in [109].

A perforated dielectric sphere, such as a solid particle [110–112], supports the excitation of whispering gallery modes (WGMs) [105,113], accompanied by the appearance of optical vortex near the particle boundary similar to topological photonics [114,115] (see Figure 5). Perforation of the spherical particle isolates the energy backflow regions of WGM. It was shown that the Poynting vector fields are strongly turbulent. Several characteristic topological phase defects are distinguished: phase singularity points, around which optical vortices are organized, and vortices located between the saddle zones of the phase field, where the longitudinal Poynting vector component vanishes. The influence of a nanohole

in a particle affects the “blue” shift of the resonant wavelength, the drop in the quality factor and the intensity of eigenmodes. However, by a small shift in the illuminating wavelength from the resonant value, it is possible to control the optical vortices position near the nanohole area, which, in turn, makes it possible to control the ratio of the forward and reverse optical energy flows [105]. Interestingly, when detuning the resonance, the reverse energy flow can change for a forward one near the particle surface, it is possible to implement an “optical catapult”. Moreover, when the hole diameter changes, the resonance dispersion effect occurs, i.e., a reverse energy flow and a strong field gradient occur only at Mie resonance.

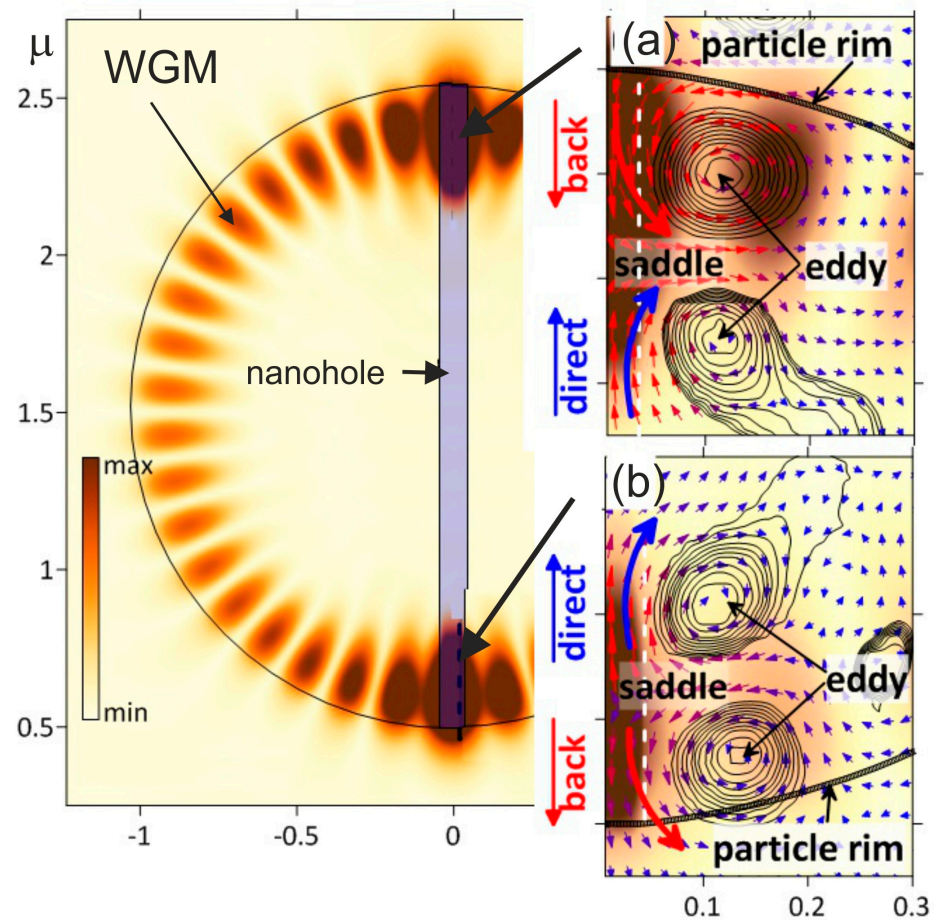


Figure 5. Direct and back energy flow structures in a nanohole structured spherical particle in the resonant mode. The radiation of a flat wavefront is incident from below. Adapted from [116].

From a practical point of view, a nano-scale hole can be drilled inside a dielectric sphere by several modern technologies [117,118]. The effects of the reverse optical energy flow can find an interesting application for microscopy [119,120] and nanoparticle trapping [121–125] in the light-analyte interaction techniques [126–132], etc.

9. Conclusions

There are a few characteristic scales for the optical phenomena in light scattering, starting from the Rayleigh scattering for particles with a small-sized parameter of $q \ll 1$ to the geometrical optics limit with a size parameter of $q \sim 100$. On the other hand, the optical properties of optical structures with a size parameter of the order of unity $q \sim 1$ attract great attention (Mie-tronics).

Above, we briefly considered some new optical effects in the scattering of light by particles with intermediate values with a size parameter of $q \sim 10$, known as mesoscale [133], which had remained a *terra incognita* in the field of optics for a long time. In a broader

context, they have attracted attention because they can support optically induced magnetic and electrical resonances when the strength of the magnetic resonance prevails over the electrical one, which underpin the emerging field of mesotronics. The field of mesotronics [21,22] is far away from the basic idea, for example, of plasmonics, and much richer, introducing its own concept and knowledge. For such a parameter size, the scattering is not caused by the interference of a single mode, also of high order multipoles, producing unusual shapes of emitted radiation. In Figure 6, a schematic image for different mesoscale ($q \sim 10$) effects in low loss dielectric particles is shown.

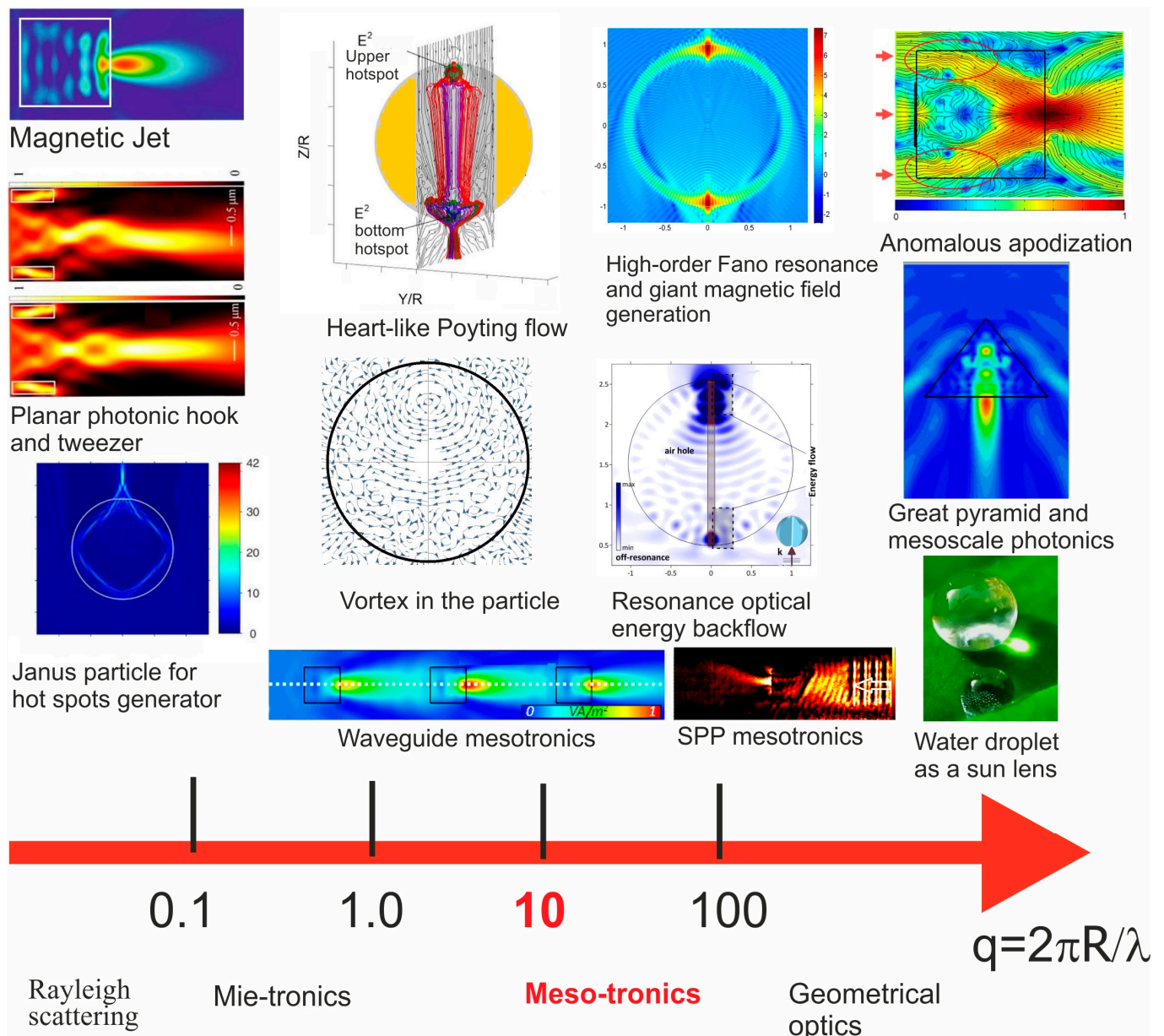


Figure 6. Schematic image for optical effects in low loss mesoscale dielectric particles [30–32,36,37].

Furthermore, such structures support the subwavelength localization of magnetic fields. Note that *plasmonics* [1–3], *meta-tronics* [13,14], *Mie-tronics* [11,12,23–25] and *meso-tronics* [21,22] do not exist separately from each other [16,22,27] but often complement each other [30–32].

A number of new optical effects have been discovered in this field in the last few years. Some physical concepts presented here and in [31,32,36,37,134,135] are very general and

their application can be extended in many ways: for instance, to the terahertz, in which the absorption is at least of 3–4 orders higher than in optics, surface plasmons and acoustics, in which the dielectric structure is always anisotropic due to two sound waves (transverse and shear). Mesotronic methods are even applicable to explain some of the effects of the Great Pyramid [136,137], square microresonators [138–140], nanopatterning [141], etc. Moreover, for example, the use of “waveguide mesotronics” concept [142], based on the mesoscale particle chain with periodical focusing modes through air gaps, makes it possible to double the propagation length [143,144] of plasmon waves [145]. Note that the concept of a waveguide based on closely placed spherical particles [146–153] does not have such capabilities [31].

However, we are glad to note that many of these concepts are now an experimental reality. We believe that the best time for mesotronics is yet to come. Moreover, though they are difficult to predict, we will witness many new discoveries in mesotronics.

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