We study the formation of the electric and magnetic near-field hotspots in dielectric cylindrical dimers. We compare dielectric and metallic dimers by using experimental data for all materials and consider both TM and TE polarizations of light. We demonstrate that dielectric dimers allow us to simultaneously achieve pure magnetic and electric near-field hotspots for both polarizations in contrast to plasmonic structures. This offers new approaches for near-field engineering such as sensing, control of spontaneous emission, and enhanced Raman scattering.

In the last decade, nanoplasmonics attracted a lot of attention due to its ability to generate strong near-field enhancement by using metallic nanoscale structures. Such electromagnetic field enhancement has been actively studied using clusters of nanoparticles created from different materials. Plasmonic nanoparticles with various geometries have been reported to control the behaviour of light in the near-field region.\(^1\)\(^{13}\) However, plasmonic structures suffer from strong dissipative losses in metallic components, even far from any resonances.\(^14\) Recently, it was suggested that dielectric materials offer competitive alternatives to plasmonic counterparts allowing us to reduce the dissipative losses.\(^15\) At the same time, the ability to achieve such a level of near-field enhancement comparable with plasmonic nanostructures, is still a challenge.\(^16\)\(^{19}\) To address this, we analyse and design optimal dimer configurations to achieve the strongest near-field enhancement in the visible regions by using realistic experimental data of the materials.\(^20\)\(^{21}\) We demonstrate that by using dielectric materials, it is possible to create both electric and magnetic hotspots comparable with plasmonic structures in TE polarization (a magnetic field parallel to the axis of nanowires). We also show the possibility to achieve near-field enhancement in TM polarization with dielectric nanowires, which is not possible by using metallic materials, and, finally, introduce pure magnetic and electric hotspots both together simultaneously by using dielectric cylindrical dimers.

The comparative analysis of both dielectric and metallic dimers provides us with a complete understanding of the optical response of such structures. For our purposes we choose silicon and silver as two commonly used dielectric and plasmonic materials, respectively. To simplify our analysis we focus on a symmetric dimer configuration and assume that the nanowires are made of the same material, with same diameter and also placed symmetrically around the origin.\(^22\) Two-dimensional general arrangement of dimer's elements (nanowires) is shown in Fig. 1. The incident planewave is illuminating in the \(x\) direction with either TE or TM polarization.

For TE polarization, the incident planewave can be written as
\[
\mathbf{H}^\text{inc} = \hat{a}_\text{e} H_0 e^{-i2\pi n_1 r \cos(\phi)}
\]
where \(\phi\) is the polar angle in the cylindrical coordinate. We use the multipole expansion method to describe the interaction of light with nanowires.\(^23\)\(^24\) The total field of an individual nanowire can then be presented as
\[
\mathbf{H}_l = \hat{a}_\text{e} H_0 e^{-i2\pi n_1 r \cos(\phi)} \left[ t_l J_n(\beta_l r) + \rho_n H_{n-1}^{(1)}(\beta_l r) \right]
\]
where \(\beta_l = 2\pi l^{-1}[\epsilon(\lambda)]^{\frac{1}{2}}\), \(H_0\) is the incident planewave amplitude, \(J_n\) and \(H_{n-1}^{(1)}\) are the \(n\)th order Bessel and Hankel functions of the first kind, respectively; \(n\) is the mode number, \(l\) is the number of the layer which is 1 for the nanowires material and 2 for the surrounding material which is air, \(\epsilon(\lambda)\) is the dielectric constant of the \(l\)th layer at wavelength \(\lambda\), \(r\) is the radius. Coefficients for partial waves in the \(l\)th layer \(t_l\) and \(\rho_n\) are found by solving the boundary condition equations for the tangential components \(H\) and \(E_y\). In addition, we put \(\rho_n = 0\) to avoid singularity of Hankel functions at the origin, and \(t_n = 1\) for each mode to describe the incident planewave expansion through the cylindrical waves. For TM polarization, an expression similar to eqn (1) can be written for \(E_{\text{total}}\) and the expansion coefficients can be found by solving the boundary value problems with respect to tangential components, \(E_z\) and \(H_\phi\).
In the first step we solve the boundary condition equations for individual wires separately and find the expansion coefficients.\(^{23,24}\) The tangential fields, \(H_z\) and \(E_y\) for TE polarization and also \(E_z\) and \(H_y\) for TM polarization should be equal for every mode on both sides of the boundary of the nanowires and air in \(r = R\). Solving these boundary value equations gives us \(\xi_n^i\) and \(\rho_n^i\) coefficients. In the second step we employ the multiple scattering problem solution, to consider the interaction between the nanowires.\(^{32,37,24}\) In this case, the scattered field from one cylinder becomes an incident wave on another in addition to the incident planewave. Using the translation additional theorem, we can rewrite the scattered fields in the form of the Hankel function in the new form of a superposition of incident Bessel functions as in ref. 29:

\[
e^{-i\theta}H_n(\kappa r) = (-1)^n \sum_{m=-\infty}^{\infty} H_{m+n}(kd)J_m(\kappa r)e^{i\theta},
\]

where \(\theta\) is the angle between the nanowires centre-to-centre line and the direction of each centre to the observation point.\(^{32}\) This procedure leads the modified expansion coefficients \(\phi_n^i\) of each nanowire in the case of multiple scattering between two cylinders. Then, we are able to obtain the outside field close to the nanowires to analyse near-field enhancement. In a similar way, we calculate the fields inside the dimer by modifying \(\xi_n^i\) coefficients for each nanowire satisfying the appropriate boundary conditions.

As the next step, we search for the optimized parameters to maximize the field's amplitude in the middle of the dimer's gap to form enhanced hotspots using a genetic algorithm (GA), which is based on random numbers generation and search all around the parameter space to find the global extremum.\(^{30-33}\) We use our GA\(^{34}\) and define a fitness function in the middle of the gap as

\[
f(R, \lambda, d) = \max[\text{FieldAmplitude}(R, \lambda, d)],
\]

where \(R\), \(\lambda\) and \(d\) are the nanowire radius, the wavelength and the centre-to-centre distance, respectively, which also are the optimizing parameters in this work. ‘FieldAmplitude’ is chosen as \(|H_z|\) or \(|E_{\text{trans}}|\) in TE and \(|E_z|\) or \(|H_{\text{trans}}|\) in TM polarization. We restrict the wavelength range, started from 300 nm to 900 nm to cover the visible region. The radius is changing in a wide range from 10 nm to 200 nm. We also confine the gap size \((d - 2R)\) to be smaller than 50 nm to stay away from diffraction effects. Also, to prevent the tunnelling effect in plasmonic dimers,\(^{35}\) we start the gap size from 3 nm.

We analyse two different directions of the dimer’s axis, parallel and perpendicular to the direction of the incident plane-wave propagation. The optimization is done for two different types of materials, dielectric (silicon) and metallic (silver) structures separately. Tables 1 and 2 illustrate the optimization results for electric and magnetic hotspots in two cases of dimer orientation. The optimized values in the last row of Tables 1 and 2 are achieved by using the optimized radius, gap size, and the wavelength illustrated in the previous rows. The summary of the results is demonstrated schematically in Fig. 1.

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**Fig. 1** Schematic near-field hotspots excitation in dielectric and metallic dimers. Panels (a–d) and (e–h) demonstrate hotspots in TE and TM polarizations respectively. The dimers are shown in two perpendicular and parallel arrangements with respect to the direction of the propagation of the incident wave. Panel (a) demonstrates that for dielectric nanowires, it is possible to separate magnetic and electric hotspots. The small shift of hotspots’ location from the centre of the gap is shown in panels (a, e). The shift becomes smaller with almost overlapped magnetic and electric hotspots in the plasmonic case, as demonstrated in panel (c). Panels (a, c, e) show that the direction of the locational displacements of magnetic and electric hotspots are opposite in dielectric and plasmonic dimers. Note that such hotspots do not exist for TM polarization in metallic nanowires.
which also shows the position of the electric and magnetic hotspots in dielectric and metallic dimers separately.

Tables 1 and 2 reveal interesting facts about the hotspots in cylindrical dimers. For TE polarization, electric and magnetic hotspots are achievable with almost lossless dielectric dimers, comparable with plasmonic ones. The results also show that for TM polarization, it is possible to obtain strong hotspots by dielectric dimers, which is not possible using plasmonic material.

Moreover, by analysing the near-field profiles, which are schematically presented in Fig. 1, we reveal that the hotspots are not exactly in the middle of the gap in perpendicular arrangement. In particular, Fig. 1(a) shows that in dielectric dimers, the location of the magnetic hotspot is shifted toward the \(+x\) direction, with respect to the middle of the gap (the same as Fig. 1e). The electric hotspot in this dimer is shifted in the opposite direction. It is interesting to note that the shifts of the location of the hotspots in plasmonic dimers are reversed, as can be seen from Fig. 1(c). However, the amount of these shifts in plasmonic dimers is smaller and the two hotspots have overlapped fields in the middle.

Now we analyse the hotspots and their local shifts in both dielectric and plasmonic dimers, presented in Fig. 1(a, c, and e). All three figures indicate that the local shift of magnetic and electric hotspots are opposite for dielectric and plasmonic dimers independent of the polarization. To have more in depth interpretation of Fig. 1(a), we plot the field profile of two different dimers with optimized electric and magnetic hotspots with TE and TM polarizations in Fig. 2(a) and (b), respectively. The dimer element parameters are shown in the second and fourth columns of Table 1, respectively. In the dielectric dimer, the magnetic field intends to remain mainly inside the dimer elements; however, Fig. 2(b) shows that the magnetic field has considerable field amplitude in the gap region.

Fig. 2(a) and (b) demonstrate that the maximum of the absolute value of the fields is more than the optimized results shown in Table 1. The reason is that Table 1 presented the

![Fig. 2](image-url)
optimized values in the middle of the gap. In Fig. 2(c) we show the exact location of the hotspots and the field distribution around it, along the line perpendicular to the dimer’s axis passing through the centre of the gap. Similar results are shown for plasmonic dimers in Fig. 3. Fig. 3(a) and (b) show the electric and magnetic hotspots for two different silver dimers, based on the results in columns six and five of Table 1, respectively. Comparison between Fig. 2(c) and 3(c) reveals that the amounts of the local shifts of the hot spots from the centre of the gap are much less in plasmonic dimers compared to dielectric ones. The magnetic and electric hotspots almost overlap in the middle of the gap in plasmonic dimers as demonstrated in Fig. 1(c).

The results shown in Fig. 2(c) and 3(c) reveal another interesting fact that the electric field becomes near zero in a region close to the electric hotspot, making two maximized and minimized electric field strength points close to each other. This becomes more interesting in the case of dielectric dimers, where this zero electric field point, overlaps the magnetic hotspot. This means that the magnetic hotspot in dielectric cylindrical dimers is pure magnetic. Fig. 4 compares the electric and magnetic field profiles in the dimer shown in Fig. 2(a) which also demonstrates a similar pure electric hotspot with a near zero magnetic field. To gain a deeper insight into the origin of how these hotspots are formed, we present mode decomposition of the dimer and analyse the dominant mode contribution to the formation of the corresponding hotspots, which are created by the interference of different overlapping harmonics.

First, we note that the behaviour of the harmonics in a dimer is quite different from a similar single particle. To explain the behaviour of different modes, we analyse the dimer shown in Fig. 4 (same as Fig. 2a) as an example of dielectric dimers. We plot the spectrum of the dimer’s extinction cross section (ECS) for different modes in Fig. 5, by changing the gap size in the range of very close (3 nm gap) to very far (single wire limit) elements. ECS can be calculated by having the expansion coefficients \( \rho_n^{air} \) and \( \rho_n^{air} \) of the nanowire one and two, respectively, from eqn (1) by solving the boundary conditions and using the multiple expansion method. Using the relation ECS\(_n\) = \( \frac{2\lambda}{\pi} \) Real\( \{\rho_n^{air} + \rho_n^{air}\} \) and also ECS\(_\text{total}\) = \( \sum_{n=-\infty}^{n=\infty} \) ECS\(_n\), we normalize the ECS value to \( \frac{2\lambda}{\pi} \) (introducing NECS). Fig. 5 shows the spectrum of the NECS of the first four modes plus the total NECS using the modes from \( n = -30 \) to \( n = +30 \). In this figure one can clearly see the revival of the scattering intensity of various modes at the corresponding resonances by increasing the gap size. Such revivals are associated with the diffractive coupling between the particles.\(^{13}\) The optimal conditions for the enhanced hotspot are indicated by white arrows in Fig. 5 and are associated with the resonant near-field excitation of the octupole mode, which does not exhibit such revival features with the increasing gap size. It indicates the peculiarity of this mode in the formation of the near-field hotspot. Another interesting feature is a strong blue shift of the collective magnetic dipole spectrum by decreasing the gap size while the other harmonics do not experience critical changes but quite small separation.

The variation of the NECS resonance amplitudes by changing the gap size is associated with the refraction effect in the case of having the gap size comparable with the wavelength. This is affected by the spectral shifts in magnetic dipole mode and consequently the total ECS. The far-field radiation pattern and the scattered field profile are also shown in Fig. 5(f) indicating the forward directional scattering properties of the dimer. The demonstrated far-field pattern radial values are normalized to those of a single nanowire, indicating the directivity gain with respect to a single nanowire with the same specification.

Second, in Fig. 6 we show the real part of the magnetic field profile of the first four harmonics in the same silicon dimer. The amplitude of the higher modes becomes smaller in comparison with the showed modes. The dimer’s axis is

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**Fig. 3** The field profile of two different silver dimers optimized for their (a) electric and (b) magnetic hotspots, based on the results in the sixth and fifth columns of Table 1, respectively. Panel (c) shows the field distribution along the x axis, and the location of the hotspots in the structures of panels (a) and (b). The incident plane wave is illuminating in the x direction and the field values are normalized with respect to the absolute value of the incident fields.

**Fig. 4** The electric and magnetic field profiles of the silicon dimer shown in Fig. 2(a) optimized for its electric hotspot based on the results in column two of Table 1. The figure compares the locations of the hotspots and demonstrates their electric and magnetic purity. The fields’ amplitude values are normalized to those of the incident wave.
perpendicular to the direction of the propagation and both nanowires are excited in phase. As a result of this symmetry, the expansion coefficients \( \rho_l \) of one cylinder are equal to \( \rho_l - n \) of the other one. The structure is the same as the one in Fig. 2(a), but the magnetic field is plotted instead of the electric one which is much weaker than the magnetic field inside the structure. In this structure, the dominant mode is \( n = \pm 3 \), in both far- and near-field regions, while for instance, for the dimer described in the column four of the same table, the quadrupole harmonic is dominant.

We note that the above investigated silicon dimer is optimized for the electric near field enhancement, based on the descriptions in column two of Table 1, which indicates that the behaviour of the resulting magnetic hotspot is not necessarily optimal. This generally applies to the introduced designs in both Tables 1 and 2.

In conclusion, we used the multipole expansion method to analyse dimers made from dielectric and plasmonic nanowires. We studied two different configurations of dimers, with their axis parallel/perpendicular to the direction of the incident wave propagation. We investigated both electric and magnetic hotspots and analysed different harmonics and their interaction with the dimers.
behaviour by making the dimer elements closer starting from a single nanowire. The displacement of the hotspots from the centre of the gap is also analysed in detail. We showed that for electric/magnetic hotspots in dielectric dimers, there is a point on the other side of the gap with zero amplitude of the same field (electric/magnetic), which overlaps the hotspot of the other field (magnetic/electric). This leads to the formation of both pure magnetic and electric hotspots on the opposite sides of the gap. All the results are analytically achieved using the first 30 harmonics. The optimized designs have also been presented for all the cases separately using a genetic algorithm. These results offer new approaches for near-field engineering of a variety of applications.

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