Electromagnetically induced transparency based on magnetic toroidal mode of dielectric reverse-symmetric spiral metasurfaces

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Abstract
The intriguing properties of the toroidal mode (TM) resonance can potentially promote a low-loss light–matter interaction. This study proposes an electromagnetically induced transparency (EIT) resonance with a high quality factor, which can reach 7798, and low mode volume can reach $0.009 \, \mu m^3$, high contrast ratio can reach nearly 100%, in the near-infrared region, which is generated by the magnetic TM in a reverse-symmetric coupling spiral metasurface. A two-oscillator model can only explain the influence of near-field coupling at the EIT point for weak coupling. Moreover, a multipole decomposition method shows that the excitation mechanism of EIT resonances originates from the destructive interference between the subradiant modes (magnetic toroidal dipole-electric quadrupole) and magnetic dipole resonance. Consequently, a new general extinction spectrum interference model is applied to fit all coupling conditions for both weak and strong coupling results that perfectly correspond to the multipole decomposition method. The results of this study could be useful in the analysis and understanding of the electromagnetic coupling characteristics of nanoparticles and provide a design approach for novel metasurfaces for low-loss optical applications.

1. Introduction
Electromagnetically induced transparency (EIT) resonances is a special case of Fano resonances with sharp lines, which play a key role in various applications, such as in nonlinear optics [1], supersensitive sensors [2, 3], lasers [4], and optical switching [5–7]. The physical mechanism of EIT, similar to Fano resonance, originates from the coupling effect of dark and bright modes. EIT can be viewed as a special phenomenon when the frequencies of broad and narrow spectrum resonances match each other [8]. Many plasmonic metamaterials supporting Fano and EIT resonances provide strong electromagnetic field confinement at a deep sub-wavelength scale [9]. However, these metamaterials have two disadvantages: first, an electric resonance is stronger than a magnetic resonance, which can cause stronger radiation losses. Second, the intrinsic Ohmic loss cannot be ignored, especially in the optical or near-infrared regions [2]. These disadvantages hinder the use of these materials in photonic integrated circuits or nonlinear applications that require high confinement and low losses. By contrast, a promising solution for all-dielectric metasurfaces composed of high-refractive-index and low-loss materials can support electrical and magnetic resonance with strong light confinement, small dissipation, and low thermal conductivity [10]. It is possible to flexibly design the novel magnetic resonance optical phenomenon; this has been widely studied, for example, in optical cloaking [11–13], dichroism [14], complete reflection [15, 16], and narrowband filtering [17]. However, the incident electromagnetic field is localized inside dielectric particles, which is not conducive to an interaction with the external environment [18]. A split gap can be introduced to enhance the near field...
to the outside of the nanocavity. However, this will cause energy leakage and a rapid decay in the high quality factor (Q-factor) [18, 19].

Recently, high electromagnetic field confinement, small radiation loss, and weak coupling in the free space of toroidal mode (TM) have attracted a lot of significant attentions [20–22]. Together, an electric dipole (ED), a magnetic dipole (MD) and a toroidal dipole (TD) constitute a basic electromagnetic excitation [23]. Recent applications take advantage of such properties in nanoswitches [5, 17] and enhanced nonlinear effects [1, 24]. In addition, there have been extensive investigations in exploring of the instrumentation techniques of toroidal metastructures toward high-performance metadevices, such as polarization converters [25, 26], low threshold nanolaser [4] and ultrasensitive immunobiosensors [27]. However, a TD cannot be represented by a standard multipole expansion and is often masked by much stronger ED and MD resonances, making its characteristic response extremely challenging [28, 29]. The most basic TM components are a magnetic toroidal dipole (MTD) and an electric toroidal dipole (ETD) [30]. Specifically, the ETD is produced by a polar current (current flowing along the torus meridian) and is equivalent to a closed loop of magnetic dipoles in a head-to-tail arrangement. Similarly, MTD can be regarded as a closed loop of electric dipoles in a head-to-tail arrangement [26, 30]. Hence, MTD and ETD exhibit a high electromagnetic field confinement, small radiation loss, and weak coupling in free space [31], which is conducive to the formation of resonance with a high Q-factor [32]. Some reports have been published on ETD Fano [33–35] and EIT resonance [17]. However, so far, there are only a few studies on the realization of MTD EIT resonance.

This study proposes an all-dielectric metasurface with an MTD to support EIT with a high Q-factor resonance in the near-infrared region. The metasurface is composed of a periodic reverse-symmetric coupled dielectric spiral. The near-field distribution of the MTD indicates that the energy is strongly localized at the EIT peak point. A proposed model is applied to analyze the transverse coupling in the two-oscillator model (TOM) to understand the EIT mechanism. For further suitability to strong coupling conditions, a multipole decomposition shows that the EIT resonance is caused by the destructive interference among the sub-radiant modes (MTD-electric quadrupole (EQD)) and the MD resonance of radiation. Then, a more general EIT extinction spectrum interference model (ESIM) explains the underlying physics and all simulated results of a finite element method. The EIT resonance reveals the complexity and diversity of the near-field coupling of electromagnetic modes in a dielectric coupled spiral structure. The intriguing properties of EIT may potentially facilitate light–matter interaction at a sub-wavelength scale, such as in sensors and slow light.

2. Simulation results and theoretical analysis

The MTD metasurface is composed of two periodically arranged Archimedes spirals of silicon (the refractive index of silicon was taken from reference [36]) placed over a standard silica substrate (refractive index $n_{SiO_2} = 1.45$), as shown in figure 1. The two spirals have a 180° rotational symmetry about the z axis. The geometric parameters of the metasurface in figures 1(a) and (b) are as follows: substrate height $H = 400$ nm, period $P_x = P_y = 900$ nm, inner radius $r = 5$ nm, spiral arm width $w = 45$ nm, gap $g = 21$ nm, the silicon thickness $h = 112$ nm, distance between two spiral centers $d = 208$ nm, desired number of turns $n = 2.5$, spiral growth rate $b = (w + g)/(2\pi)$. A unit cell of the metasurface is simulated using COMSOL Multiphysics®, a commercial software, and a finite-difference time-domain software from Lumerical Solutions. The unit cell is surrounded by air and excited by a plane wave polarized along the x axis with a propagation vector along the negative z axis. Floquet-periodic boundary conditions and perfectly matched layers are applied to the x–z and y–z planes and z axis, respectively.
Figure 2. EIT response of the metasurface. (a) Simulated reflection (blue lines) and transmission (red lines) spectra of the metasurface. (b), (d), and (f) Normalized magnetic field profile at dip1, dip2, and peak in the $x$–$y$ plane bisecting the spiral metasurface. The color maps and black cones at EIT dip and peak spectral positions represent $|H|/|H_0|$ and magnetic field vector profile, respectively. The black arrows show the directions of the magnetic field. (c), (e), and (g) Normalized electric field profile at dip1, dip2, and peak in the $y$–$z$ plane bisecting the spiral metasurface. The color maps and black cones at EIT dip and peak spectral positions represent $E_z$ and electric field vector profile, respectively. The red arrows show the directions of the electric field. (h) Artistic image of MD generated because of the circulating current. (i) Artistic image of MTD generated because of the circulating electric field produced by a magnetic induction in the spiral configuration.

Table 1. The list for the performances of metasurface Q-factor including type of metasurface.

| References | Year | Type of metasurface          | Q-factor |
|------------|------|------------------------------|----------|
| [37]       | 2020 | Spoof surface plasmons EIT   | <100     |
| [39]       | 2019 | EIT resonance                | 270      |
| [2]        | 2019 | ETD Fano resonance           | 3189     |
| [17]       | 2020 | ETD–EIT resonance            | 4364     |
| [40]       | 2021 | Fano and EIT resonance–BIC   | 1370/816 |
| [10]       | 2021 | TD Fano resonance–BIC        | 120000   |
| This work  | —    | MTD–EIT resonance            | 7798     |

The numerically calculated reflections and transmissions are shown in figure 2(a). An EIT with a high Q-factor (the ratio between the resonant wavelength $\lambda_0$ and the full width at half-maximum $\Delta \lambda$ of a transmission peak) of 7798 is realized in the near-infrared region, which is much higher than the Q-factor in the latest reported plasmonic [37, 38] and all-dielectric metasurface studies [39, 40], as depicted in table 1. The effective mode volume is calculated according to standard Purcell definition by using the COMSOL Multiphysics, $V_{\text{eff}} = \int_V \varepsilon(r)|E(r)|^2 dV / \max \left[\varepsilon(r)|E(r)|^2\right]$ [41], where $\varepsilon(r)$ is the dielectric constant, $E(r)$ is the electric field strength and $V$ is a volume encompassing the resonator with a boundary in the radiation zone of the cavity mode. According to the above expression, the numerically calculated normalized effective mode volume of MTD–EIT is 0.009 $\mu$m$^3$. The low mode volume and optimized $Q/V_{\text{eff}}$ metasurface reveal enhanced sensitivity for ultrathin analyte overlay deposited on the metasurface, indicating that the designed metasurface is expected to enhance light–matter interactions. The spectral contrast ratio $|T_{\text{peak}} - T_{\text{dip}}| / |T_{\text{peak}} + T_{\text{dip}}| \times 100\%$ reaches approximately 100%, where $T_{\text{peak}}$ and $T_{\text{dip}}$ are the peak and dip values of the EIT resonance, respectively. To explore the EIT resonant responses more thoroughly, the electric field and magnetic field distributions of the EIT dip1, dip2, and peak (marked in figure 2(a)) are shown in figures 2(b)–(g). As shown in figures 2(b)–(e), the magnetic field for the two dips of the EIT resembles the MD resonance along the $y$ axis in figures 2(b) and (d) (black arrows) [32, 42]. The electric field shows two weak opposite EDs with an insignificant coupling, as seen in figures 2(c) and (e) (red arrows). At the peak, figure 2(f) shows that a couple of opposite vortex magnetic fields cause two robust EDs (figure 2(g) with red arrows) to form the MTD (an artistic representation of figure 2(i)). In essence, although the electric field distribution forms a vortex in the two dips (figures 2(c) and (e)), its strength is not sufficient to form the MTD. Therefore, the high Q-factor of the EIT resonance is effectively from the excitation of the MTD and MD destructive interferences to suppress the radiation loss and non-radiative Ohmic loss [43, 44], which is different from previous studies of plasmonic spiral structures.
Figure 3. (a) Schematic diagram for the EIT in a prototype classical three-level system. (b) Simulated transmission spectra of single US (green solid line), DS (red solid line), and coupling spiral of the EIT (blue solid line) metamaterial structures. The black star indicates the origin coordinates.

Figure 4. (a) Transmission with numerical simulations (blue solid line) and theoretical calculations (red dashed line) with \( d \) varying from 178 to 208 nm. (b) Extracted FEM numerical simulations coupling parameters and damping as a function of lateral displacement \( d \) according to formula (1)—\( \text{Im}\{\xi\} \). (c) Correspondingly draw the electric field line distribution diagram on the color diagram of the magnetic energy density (logarithmic scale) at the resonance peaks of \( d = 208 \) nm, \( d = 190 \) nm, and \( d = 178 \) nm.

To further understand the underlying physical properties of the two modes, a theoretical model is introduced in the following section [37, 47].

The physical characteristics of the EIT can be analogized as an atomic system in figure 3(a) [48, 49]. \( |0\rangle \) is the ground state. Two higher states \( |1\rangle \) and \( |2\rangle \) are assumed to be the down spiral structure (DS) and the upper spiral structure (US), respectively. \( |0\rangle - |1\rangle \) and \( |0\rangle - |2\rangle \) are considered to be the excitation of the bright and dark modes in the EIT system. The transition rate \( \kappa \) between states \( |1\rangle \) and \( |2\rangle \) is related to the coupling strength between the two modes [48]. Consequently, in order to verify the destructive interference
recent studies [9, 50]. Successively with an increase in the bright mode and dark mode, respectively, which demonstrates that the destructive interference of two oscillator DSs and oscillator USs, respectively. Therefore, the resonances of DS and US are regarded as that the transmission of the DS has a resonant dip at 1084 nm, whereas the transmission of the US does not between the DS and the US, their transmissions are calculated, as shown in figure 3(b). It is clearly observed that the electromagnetic wave is expressed in terms of the displacement as [37, 47]:

\[ P = \int \mathbf{j} d^3r \]

\[ M = \frac{1}{2} \int \mathbf{(r \times j)} d^3r \]

\[ T = \frac{1}{2} \int \mathbf{[(r \cdot j - 2r^2)]} d^3r \]

\[ G = -\frac{1}{2} \int r^2 (r \times j) d^3r \]

\[ Q_{\alpha\beta} = \frac{1}{2} \int \mathbf{[r \times j_\alpha + r_j \times j + \frac{2}{3} \delta_{\alpha\beta} (r \cdot j)]} d^3r \]

\[ M_{\alpha\beta} = \frac{1}{2} \int \mathbf{[(r \times j) r_\alpha + r_\alpha (r \times j)]} d^3r \]

\[ \mathbf{[1]} \]

\[ \mathbf{[2]} \]

\[ \mathbf{[3]} \]

where \( E \) and \( \mathbf{B} \) are the incident electromagnetic field, \( \mathbf{q}_b \) and \( \mathbf{q}_d \), \( m_b \) and \( m_d \), \( \omega_b \) and \( \omega_d \), and \( \gamma_b \) and \( \gamma_d \) represent the effective charges, effective masses, resonance angular frequencies and damping rates of the oscillator DSs and oscillator USs, respectively. \( q_d = q_d / A \) and \( m_d = m_d / B \) are substituted into the coupled differential equations (1) and (2). After solving equations (1) and (2), the effective electric polarizability of the electromagnetic wave is expressed in terms of the displacement as [37, 47]:

\[ \xi_{\text{eff}} = \frac{\mathbf{q}_b \mathbf{S}_b + \mathbf{q}_d \mathbf{S}_d}{\varepsilon_0 E} = \xi_R + i \xi_I = \frac{K}{A^2B} \left[ \frac{A (B + 1) \kappa^2 + A^2 \left( \omega^2 - \omega_d^2 \right) + B^2 \left( \omega^2 - \omega_b^2 \right)}{\kappa^2 - \left( \omega^2 - \omega_b^2 + i \omega \gamma_b \right) \left( \omega^2 - \omega_d^2 + i \omega \gamma_d \right)} \right] = \frac{A^2 \gamma_d + B \gamma_b}{\kappa^2 - \left( \omega^2 - \omega_b^2 + i \omega \gamma_b \right) \left( \omega^2 - \omega_d^2 + i \omega \gamma_d \right)}, \]

where \( \xi_R \) represents the dispersion and \( \xi_I \) gives the absorption within the medium. The simulated transmission (blue solid line) and fitting curve (red dashed line) are shown in figure 4(a). It is evident that the analytical fitting curve is in good agreement with the simulation results. The results show that the EIT is from the coupling between the DS and US modes. In figure 4(b), the coupling strength \( \kappa \) decreases successively with an increase in \( d \) from 178 to 208 nm, which can reduce the loss and is consistent with recent studies [9, 50]. \( \gamma_d \) decreases exponentially as \( d \) increases from 178 to 208 nm, whereas \( \gamma_b \) has a negligible change. In addition, \( \gamma_d \) is nearly 2228 times smaller than \( \gamma_b \) at \( d = 208 \) nm, which indicates that

![Figure 5. Scattered power (logarithmic scale) for the six major multipole moments including the ED, the MD, \( x \) component of the MTD (MTDx), EQD, and MQD.](image-url)
Figure 6. (a) Transmission calculated with FEM numerical simulations (blue solid line) and theoretical calculations (red dashed line) with \(d\) varying from 178 to 208 nm. (b) Extracted FEM numerical simulations frequency \(\omega_j\) and damping \(\Gamma_j\) as a function of lateral displacement \(d\) according to formula ESIM. (c) FEM numerical simulations for scattering power of MTD\(x\) and \(Q = \omega_j/\Gamma_j\) as a function of lateral displacement \(d\).

the radiation damping in the metasurface system is significantly suppressed [51]. Therefore, \(\gamma_d\) has a significant influence on the \(Q\)-factor of the EIT. The three typical magnetic energy density distributions of the EIT are shown in figure 4(c). The magnetic energy density decreases as \(d\) decreases, and rapidly dissipates in the background medium. However, there is a deviation in the off-resonant region of the simulated and fitted curves, especially in the case of a strong coupling (e.g., \(d = 178–184\) nm). A new effective method must be introduced here to explain the entire band curve.

The spectral features of EIT in the transmission and reflection are analyzed in detail using a multipole decomposition approach in Cartesian coordinates to identify the individual contributions of the multipole moments toward the total scattering power of the metasurface unit cell. According to the \(\exp(i\omega t)\) convention of a harmonic electromagnetic field, the induced displacement current density inside the unit cell structure can be expressed as [52]:

\[
J = i\omega\varepsilon_0 (\varepsilon_{p,r} - \varepsilon_{b,r}) E(r),
\]

where \(\omega\) is the angular frequency, \(\varepsilon_0\) is the vacuum permittivity, \(\varepsilon_{p,r}\) and \(\varepsilon_{b,r}\) are the respective permittivity of the nanoparticle structure and the background medium, and \(E(r)\) is the electric field. The moment and scattered power corresponding to each multipole are shown in table 2, where \(\delta\) is the Dirac delta function and the subscripts \(\alpha, \beta = x, y, z\) [53–55]. The scattered powers of different multipoles are presented in figure 5. In the inset of figure 5, MD makes the strongest contribution to the peak transmission at around 1107.47 nm. The scattering powers of the EQD and MTD take the second and third places, respectively, to the EIT. Then, the combination of MTD and EQD forms a small subradiation mode and destructively interferes with the broader band MD mode to form a narrow EIT. The contributions of the MQDs are small, but not negligible for the entire band. This essentially shows why a two-oscillator method does not fit perfectly in the off-resonant region. Consequently, the nature of the resonance multipole reveals the physical mechanism of the EIT.

A more general ESIM must be applied to analyze the simulation results more clearly. The ESIM expression is \(E(\omega) = |e(\omega)|^2\) [17, 19], and \(e(\omega)\) is expressed as

\[
e(\omega) = a_r + \sum_j b_j e^{i\omega_j} \left(\omega - \omega_j + i\Gamma_j\right)^{-1},
\]
Figure 7. The transmission calculated with simulations (blue solid line) and the ESIM calculations (red dashed line) with different (a) widths of $w$, (b) gaps of $g$, (c) thicknesses of $h$, and (d) turns of $n$. (e)–(h) Extracted numerical simulations frequency $\omega_j$ and damping $\Gamma_j$ as a function of the $w$, $g$, $h$, and $n$, according to the ESIM.

where $a_i$ is the constant amplitude of the background. $b_i$, $\Gamma_i$, $\varphi_i$, and $\omega_i$ represent the amplitude, damping, phase, and resonant frequencies of each mode, respectively. Comparing the results in figure 6(a) with figure 4(a), the fitted curve and simulated transmission match well when $d$ varies from 178 to 208 nm, even in the off-resonant region. Figure 6(b) shows that the fitting frequencies $\omega_1$ and $\omega_3$ match from $d = 190$ to 208 nm. This is why the TOM method fits well in the same range as in figure 4(a). The slightly varying $\omega_2$ cannot be neglected in the fitting curve away from the EIT range. In particular, when $d < 190$ nm, the two matching modes $\omega_1$ and $\omega_3$ are separated from each other, and the EIT resonance is transformed into a Fano resonance. Notably, the damping rate $\Gamma_2$ decreases with an increase in $d$, which determines the high $Q$-factor ($Q = \omega_2/\Gamma_2$) of EIT resonance [17]. Therefore, the $d$ (or coupling strength) value has a more significant influence on the bandwidth and shape of the EIT, as shown in figure 6(c). As $d$ increases, the scattering power of MTDs and $Q$-factor increase from 149 to 1350 and from 3980 to 14060, respectively. It is confirmed that an effective excitation of the MTD can strongly confine the electromagnetic fields and suppress damping (radiation loss) [31].

To further study the dependence of the EIT on different geometric parameters and ESIM generality, numerical (blue solid line) and theoretical calculations by the ESIM (red dashed line) of different geometric parameters ($w$, $g$, $h$, and $n$) are shown in figure 7. It is clear that the theoretical calculations and numerical simulations are in good agreement. From figures 7(a)–(d), the EIT resonances show that the blue shift is because of the decrease in the effective refractive index of the structure, and the resonance intensities remain almost unchanged as $w$, $g$, $h$, and $n$ decrease. By comparing the impacts of different geometric parameters on the transmissions, we can see that the position of EIT resonances is more sensitive to $w$ and $h$, whereas the linewidth is mainly affected by $n$. Notably, the fundamental resonant frequencies of the three modes decrease with a linear increase in $w$, $g$, $h$, and $n$ (see figures 7(e)–(h)), which is consistent with the simulation results in figures 7(a)–(d). Meanwhile, the $Q$-factor is determined by $\Gamma_2$, and they are negatively correlated. Furthermore, the EIT resonance is converted to Fano resonance when the bright and dark modes have large detunings (see figures 7(a) and (e) $w = 40$ nm; and figures 7(e)–(h) $n = 1.5$). Based on these results, the position of EIT can be adjusted by adjusting the geometric parameters and maintaining the $Q$-factor of the metasurface above 10000 (see figures 7(e)–(h)), which can potentially realize the application of filters and sensors.
3. Conclusion

In this study, we proposed a metasurface based on periodical coupled spiral oscillators. The metasurface supports EIT resonance at approximately 1107.47 nm. The Q-factor of the EIT resonance reached 7798, the low mode volume can reach 0.009 \( \mu \text{m}^3 \), and the high contrast ratio reached approximately 100%. A detailed field distribution proved that the EIT resonance originates from the destructive interference between the MTD and MD resonances. In particular, the atomic EIT system and TOM describe and analyze the coupling characteristics of the EIT resonance under weak coupling conditions, and the theoretical calculations are in good agreement with the simulation results. Moreover, a multipole decomposition analysis further explains the origins of the EIT optical spectral properties, and the ESIM confirms the contribution of interference coupling between multipole resonances, which provides a more accurate and effective tool for theoretical optimization of metasurfaces in both weak and strong coupling conditions. In addition, the effect of the variation in other geometrical parameters on the EIT resonance has also been studied and well fitted by the ESIM, making our metasurfaces more suitable for potential applications. A theoretical analysis of the interference coupling and the intriguing properties of MTD resonances may potentially facilitate the optimization of optical properties and light–matter interaction at a sub-wavelength scale, such as in sensors and slow light.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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