

RESEARCH ARTICLE

Off-Resonant Chiroptical Enhancement for Enantiomeric Discrimination Through Weak Measurement

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ABSTRACT

The intrinsic homochirality of lifeforms underscores the importance of real-time and accurate enantiomers discrimination techniques in fields such as asymmetric chemical synthesis, pharmaceuticals, and life science. Conventional chiroptical techniques, however, are often limited by the need for strict spectral alignment between artificial resonators and biomolecular resonances. In addition, small biological molecules typically absorb in the ultraviolet (UV) range, where high-energy photons would break chemical bonds and risk inducing photodamage. To address the intractable issue, we propose an integrable subwavelength gratings system, dubbed “double twisted grating chiral amplifier (DTGCA)”, which leverages the principle of weak measurement to amplify the circular dichroism (CD) signals. Based on the Kramers-Kronig (KK) relations, we demonstrated a linear correlation between CD and optical rotatory dispersion (ORD) in the off-resonant spectral region far from molecules’ eigenfrequencies. In contrast to contemporary nanoantenna-based amplification which depends on electromagnetic couplings, the DTGCA enables off-resonant enantiomeric ratios discrimination with separation factor exceeding 200. Our strategy offers a promising route for detecting chiral molecules with UV or near-infrared (NIR) resonances using a visible-light-based chiroptical platform.

1 | Introduction

Chirality refers to the geometrical property whereby an object is not superimposable with its mirror image. In general, chiral molecules exist as a pair of L- and D-enantiomers and they have the same atomic formula but different spatial arrangements. The nontrivial attribute has a far-reaching impact on various fundamental disciplines including chemistry, biology and life science. Enantiomers constitute energetically degenerate states [1], thus sharing many similar physical properties (e.g., molecular weight, melting and boiling points, refractive index, etc.), yet they exhibit distinct physiological functionalities. In biological

processes, for instance, enzymes, receptors and other biomarkers can recognize enantiomers as different entities due to diverse association and dissociation responses [2]. In particular, L- and D-enantiomers of drug molecules would undergo different metabolic pathways, leading to the therapeutic effect for one and contrastively inactive or undesirable effect for the other [3–5]. Therefore, enantioselectivity plays a crucial role in asymmetric synthesis [6–8], pharmaceuticals [9, 10] and life sciences [11, 12]. It is well known that life is homochiral. DNA and RNA are composed of right-handed nucleotides and human proteins are made from left-handed amino acids [13]. Mirror-image biomolecules would function diversely from their naturally occurring counterparts

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[14, 15]. They might increase the risk of biosafety because mirror enantiomer would be significantly influential on immune recognition and activation in multicellular organisms [16, 17]. With the rapid development of synthetic biology, numerous biomolecules with arbitrary chirality can be created, whereas the unexpected impacts of mirror lifeforms are being overlooked. Indeed, a number of measurement techniques for enantiomers discrimination, such as chiral chromatography [18, 19], capillary electrophoresis [20, 21], nuclear magnetic resonance (NMR) [22, 23] and CD spectroscopy [24, 25], have been studied widely. These traditional methods, nevertheless, require bulk-scale reagents, which is prerequisite and not applicable to trace-level chiral detection.

Light-matter interaction holds promise to low-abundance and high-sensitivity chiral measurement. Recent advances in chiroptical enhancement have been extensively reported, e.g., plasmonic metasurfaces for optical chirality enhancement [26–31], dielectric metasurfaces for chirality transfer [32–38], optical cavity-based systems for sensitive spectral dip shift [39–42]. However, these techniques confront the universal issue that the central response frequency between artificial resonators and biomolecules are closely matched for expanding the optoelectronic interactions. Notwithstanding the effective demonstrations, biological small molecules (i.e., typical molecular weight < 900 Da) mainly exhibit optical response in the UV spectrum [43]. Photons in this regime may coincide with the excitation energy of organic molecules and break chemical bonds. The products of photochemical reactions may alter its optical properties and induce phototoxicity, thus conventional instruments face challenge with off-resonant CD measurement of small molecules. Optical activity of chiral molecules is characterized by not only CD but also ORD. They obey the general relationship of KK transforms [44]. Probing the connection between CD and ORD, however, is also intractable as the ORD is often featureless within off-resonant spectrum. In order to considerably amplify the dispersion signal, photonic weak measurement paves another way to achieve the off-resonant CD measurement.

In this work, we proposed a chiroptical enhancement system dubbed double twisted grating chiral amplifier (DTGCA), which consisted of two subwavelength gratings to amplify the distinction of circularly polarized (CP) light transmission of different mixture proportionality of L- and D-enantiomers. The principle is ascribed to the KK relation and photonic weak measurement [45, 46]. Through elaborate engineering of the morphological parameters, the proposed nanogratings perform orthogonally polarized states' pre- and post-selection in weak measurement. The CD and ORD indices of targeted molecules far from eigenfrequency spectrum are weak values coupled into the DTGCA system. Because of the proved linear correlation of CD and ORD in this spectral range, we observe significant CD amplification factor exceeding 200 for off-resonant enantiomers. A detailed comparison of our proposed gratings system performance with other current state-of-the-art nanophotonic-based chiral sensor were tabulated in Section S1. Benefited from miniaturization of nanogratings, DTGCA hold promises to be integrated into a point-of-care testing device. In addition, chiral molecules with either UV or NIR spectral resonance would both be detectable through our proposed visible-light-based device.

2 | Methodology

2.1 | ORD Amplification

As shown in Figure 1A, the DTGCA system consists of two subwavelength gratings facing each other: a silicon gratings fabricated on glass base and a bilayer aluminum (Al) film deposited on a glass gratings with 45° orientation. The source is incident preceding the DTGCA and the transmitted power were measured with the alternative charge coupling device (CCD). The silicon grating alters the phase difference between transverse electric (TE) and transverse magnetic (TM) polarization state [47, 48], of which we chose parameters that convert CP light into an elliptically polarized state with high eccentricity. This is achievable when the two eigenstates of the silicon gratings (parallel TE or perpendicular TM to the gratings lines) were transmitted with almost identical energy and 90° phase difference and would subsequently coincide with the two eigenstates of the bottom gratings, as shown in Figure 1C. The bottom metallic gratings were designed to exhibit a significant difference in transmission of two eigenstates [49], working as a TM polarizer (See Figure 3B). Bottom gratings can be represented with Jones matrix

$$S = \begin{bmatrix} l & 0 \\ 0 & s \end{bmatrix} \quad (1)$$

where $l \gg s$ and $l^2 + s^2 = 1$. Assuming the chiral medium rotates polarization vector by θ at non-resonant wavelength, its Jones matrix can be represented by standard rotation matrix R_θ . It can be proven that S, R_θ are not commutative ($[S, R_\theta] \neq 0$), implying the overall rotatory angle through DTGCA are no longer θ . The modified polarization vectors are

$$\begin{cases} |\varphi\rangle = SR_\theta e_{TM} = \begin{bmatrix} l \cdot \cos \theta \\ s \cdot \sin \theta \end{bmatrix} \\ |\psi\rangle = SR_\theta e_{TE} = \begin{bmatrix} -l \cdot \sin \theta \\ s \cdot \cos \theta \end{bmatrix} \end{cases} \quad (2)$$

where e_{TM} and e_{TE} are unit vectors. Their arguments (with respect to their original axes) satisfied

$$\begin{cases} \varphi := \arg |\varphi\rangle = \arctan\left(\frac{s}{l} \cdot \tan \theta\right) \\ \psi := \arg |\psi\rangle + \frac{\pi}{2} = \arctan\left(-\frac{s}{l} \cdot \frac{1}{\tan \theta}\right) + \frac{\pi}{2} \end{cases} \quad (3)$$

Simplification of ψ 's expression in (3) reveals

$$\frac{1}{\tan \psi} = \frac{s}{l} \cdot \frac{1}{\tan \theta} \ll \frac{1}{\tan \theta} \quad (4)$$

Under the condition $s \ll l$, the final rotatory angle (as shown in Figure 1C) of the polarization vectors will satisfy $\psi \gg \theta \gg \varphi$, implying the proposed DTGCA could amplify the observed chiral ORD effect.

To facilitate a better understanding of our design philosophy, it is worth noting that this work is inspired by the quantum weak measurement theory [46, 50, 51], and there exists an essential equivalence between their core physical principles.

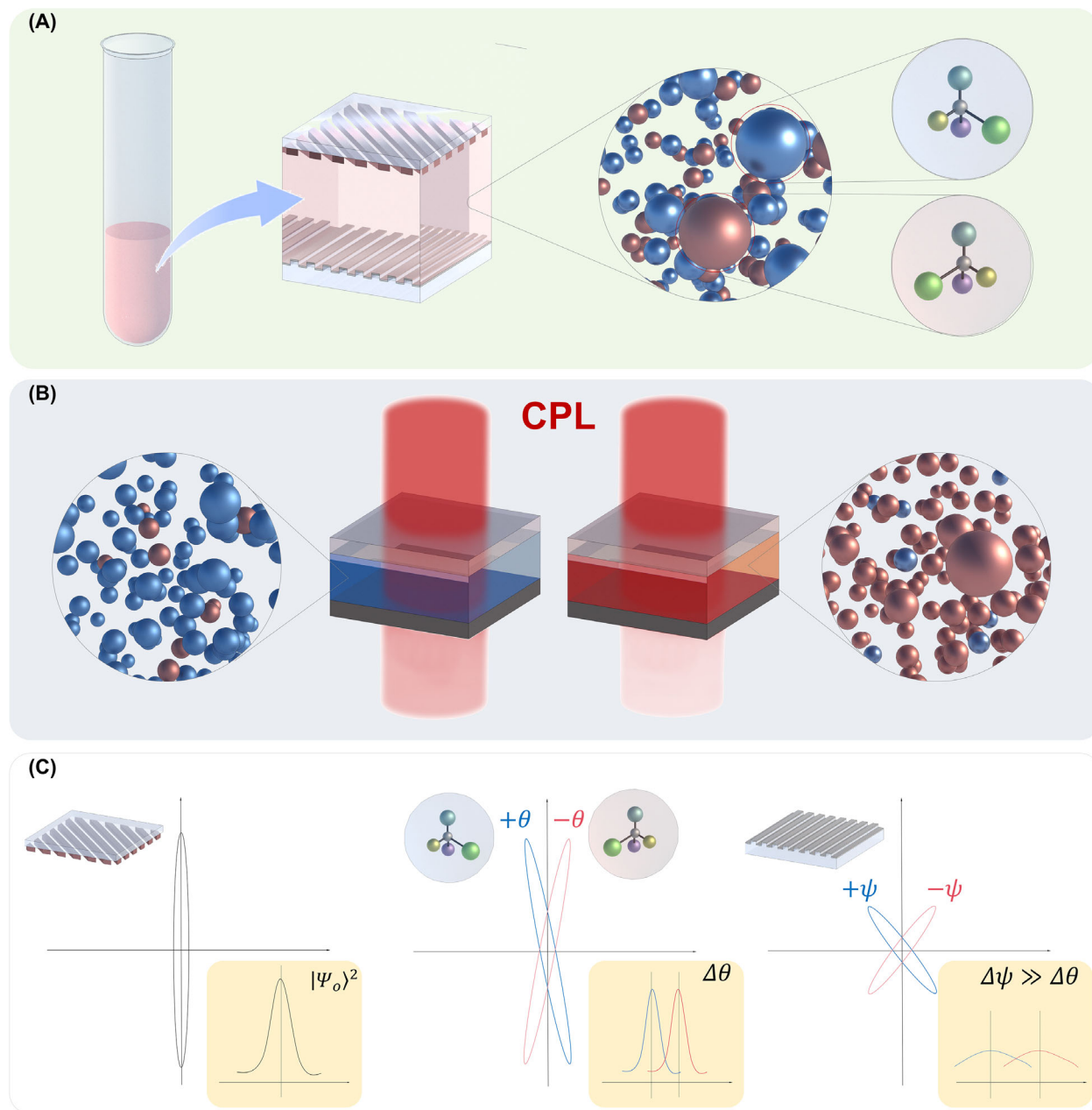


FIGURE 1 | Schematic weak measurement amplification of enantioselectivity with the proposed DTGCA: (A) A chiral solution constituted of L- and D-enantiomers mixed at certain ratio was passed through the microfluidic interlayer between two twisted gratings; (B) The difference of CP light transmission through solutions of different enantiomeric ratios were amplified through the DTGCA system (See Section 2); (C) Weak value amplification: the converted elliptical polarization state experienced ORD due to interlayer chiral medium, the rotatory angle were further amplified due to the bottom gratings' polarization selectivity.

In the context of weak measurement, the twisted top silicon gratings serve as the pre-selector, converting incoming CP light into linear polarization state parallel to either TE (y-axis) or TM state (x-axis), and the bottom metallic gratings work as the post-selector, respectively. Suppose TE state is suppressed by bottom metallic gratings, the pre- and post-selection state can, under LCP and RCP basis, be written approximately as:

$$\begin{cases} |\psi_{pre}\rangle = |y\rangle = \frac{i}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} \\ |\psi_{post}\rangle = l|x\rangle + s|y\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} l + is \\ l - is \end{bmatrix} \end{cases} \quad (5)$$

The Hamiltonians describing interaction with the measuring procedure can be represented as [46, 50]

$$H_i = -g(t) \cdot \theta \cdot \sigma_z \quad (6)$$

where $g(t)$ is the normalized instantaneous coupling rate, and σ_z is the observable spin operator coupled to the angle of linear polarization state θ with respect to y-axis. θ served as the effective measurement pointer, which is strongly correlated to the large differential transmission of the bottom metallic gratings. Slight rotation in polarization vector due to chiral ORD effect is captured by the increase in transmission measured.

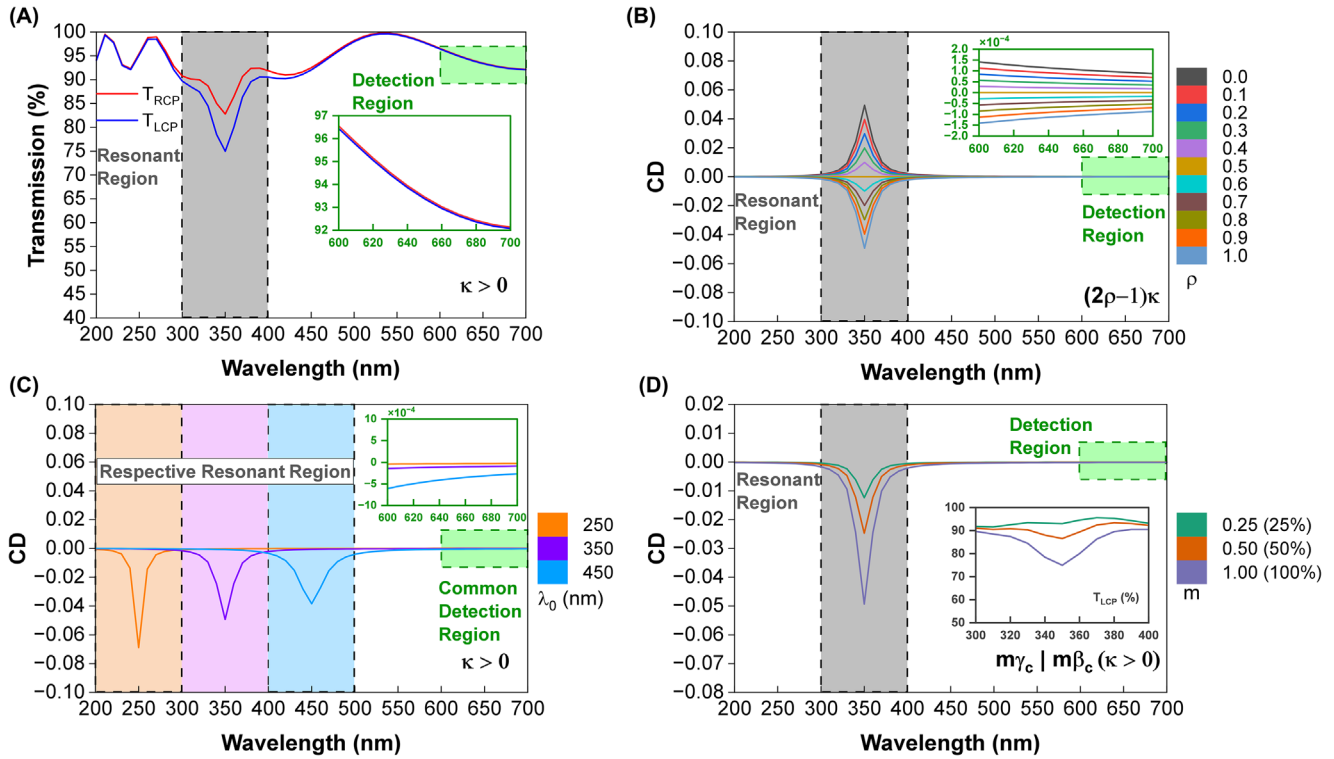


FIGURE 2 | Simulated optical transmission of chiral medium through modifying the constitutive relation. (A) CP light transmission through chiral medium with resonance wavelength set at 350 nm. Positive Pasteur parameter corresponded to weaker LCP light transmission, thus defined as L-enantiopure medium. (B) CD of different enantiomeric ratios simulated through introducing coefficient $(2\rho - 1)$, where ρ represent L-enantiomers proportionality. (C) CD of L-enantiopure medium with different resonance wavelengths. (D) CD of L-enantiopure medium at different concentrations. The concentration is controlled through manipulating absorptive and chiral coefficient at the same time. Insets in (A), (B), (C) represent magnified view at detection wavelength 600 – 700 nm, where the weak distinctions in transmission and CD are noted, and inset in (D) represents the corresponding LCP transmission of different concentrations at resonant regime, where lower concentration of L-enantiomers corresponded to higher LCP transmission (fewer L-enantiomers to absorb LCP photons), and vice versa.

The final, post-selected, state of the system after measurement over a time interval can therefore be written as:

$$\begin{aligned} \langle \psi_{\text{post}} | e^{-\frac{i}{\hbar} \int H_1 dt} | \psi_{\text{pre}} \rangle &= \langle \psi_{\text{post}} | e^{-\frac{i}{\hbar} \theta \sigma_z} | \psi_{\text{pre}} \rangle \\ &\approx \langle \psi_{\text{post}} | \psi_{\text{pre}} \rangle \langle \psi_{\text{post}} | e^{-\frac{i}{\hbar} \theta (\sigma_z)_w} | \psi_{\text{pre}} \rangle \end{aligned} \quad (7)$$

where the time-evolution of the Hamiltonian operator were applied to the pre-selected state, and $(\sigma_z)_w$ is the weak value of the observable. Accordingly, the final approximation holds when the uncertainty of the variable $\Delta\theta$ was negligible. This condition is achievable when the chiral ORD effect could be captured sensitively, which is possible with appropriately designed metallic gratings that possessed high extinction ratio. The weak value of the observable is calculated to be:

$$(\sigma_z)_w = \frac{\langle \psi_{\text{post}} | \sigma_z | \psi_{\text{pre}} \rangle}{\langle \psi_{\text{post}} | \psi_{\text{pre}} \rangle} = \frac{il}{s} \quad (8)$$

where z Pauli matrix was applied, and large weak value could be theoretically obtained.

2.2 | Correlation Between CD and ORD

In this section, the linear correlation between measured CD and ORD of chiral molecules was derived when the light source with non-resonant wavelength was used. Constitutive relation of reciprocal isotropic chiral medium was modeled as:

$$\begin{cases} \vec{D} = \epsilon_0 \epsilon_c \vec{E} + i\kappa \vec{B} \\ \vec{H} = \frac{1}{\mu_0 \mu_r} \vec{B} + i\kappa \vec{E} \end{cases} \quad (9)$$

where ϵ_c is the relative permittivity, μ_r is the relative permeability and assumed unity, and $\kappa = \kappa(\omega, \vec{r})$ is the electromagnetic coupling parameter known as Pasteur parameter. Non-zero κ couples even-parity electric fields to odd-parity magnetic fields, causing the medium to distinguish the otherwise degenerate LCP and RCP states [1, 44, 52].

κ is a complex-valued parameter with $\text{Re}(\kappa)$ related to ORD and $\text{Im}(\kappa)$ related to CD, and they were restricted by the KK relation due to causality. Homogeneous chiral medium's parameters could be theoretically expressed as Lorentzian

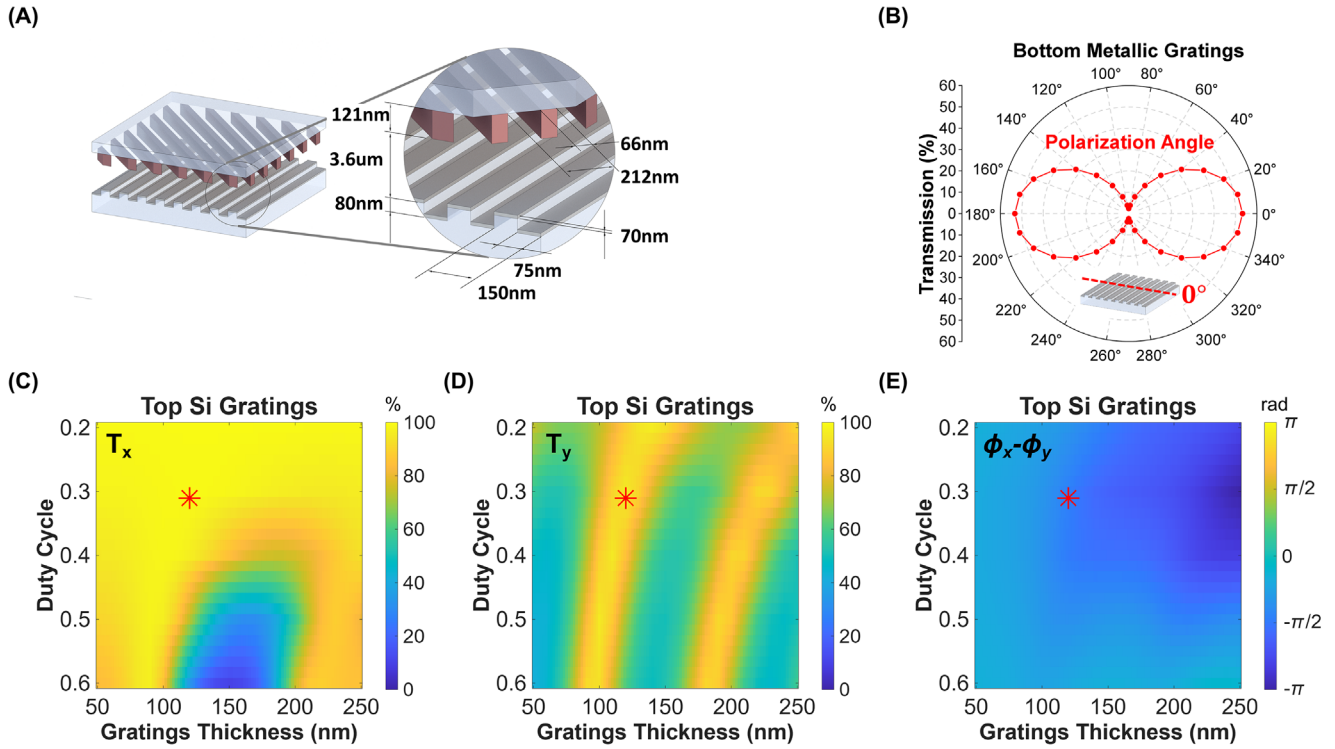


FIGURE 3 | Two twisted nanogratings configuration in DTGCA system. (A) The structural parameters of two gratings. (B) Polar plot representing transmission of linearly polarized light through bottom Al gratings. The bottom gratings effectively block polarization state parallel to gratings line. The thickness and duty cycle of top silicon gratings were swept and transmission of perpendicular TM, parallel TE polarized light, and their phase difference are mapped in (C), (D), (E) respectively. The parameters chosen for subsequent simulation were marked with red asterisk.

$$\begin{cases} \varepsilon_c(\omega) = \varepsilon_{c0} - \gamma_c \left(\frac{1}{\hbar\omega - \hbar\omega_0 + i\Gamma_{12}} - \frac{1}{\hbar\omega + \hbar\omega_0 + i\Gamma_{12}} \right) \\ \kappa(\omega) = \beta_c \left(\frac{1}{\hbar\omega - \hbar\omega_0 + i\Gamma_{12}} + \frac{1}{\hbar\omega + \hbar\omega_0 + i\Gamma_{12}} \right) \end{cases} \quad (10)$$

as described by Govorov et al. [27, 53, 54], where ε_{c0} is the background permittivity, ω_0 is the resonant angular frequency, Γ_{12} is the broadening of spectral lines, and γ_c and β_c represent the magnitudes of absorptive and chiral properties respectively. The chirality could be influenced by external factors such as temperature, pressure, coupling to nanophotonics etc. These external factors could be represented collectively by a dependence on an implicit variable τ such that $\kappa = \kappa(\omega, \tau) = \beta_c(\tau)L(\omega, \tau)$, where

$$L(\omega, \tau) = \frac{1}{\hbar\omega - \hbar\omega_0(\tau) + i\Gamma_{12}(\tau)} + \frac{1}{\hbar\omega + \hbar\omega_0(\tau) + i\Gamma_{12}(\tau)} \quad (11)$$

And the origin point $\beta_c(\tau = 0) = 0$ is chosen to coincide with region far from resonant $|\omega - \omega_0| \gg 0$. Influence of τ on κ was calculated as

$$\frac{\partial \kappa}{\partial \tau} = \frac{\partial \beta_c}{\partial \tau} L + \beta_c \frac{\partial L}{\partial \tau} \approx \frac{\partial \beta_c}{\partial \tau} L(\omega, 0) \quad (12)$$

The approximation is made around neighborhood of $\tau = 0$, where the conditions weak chirality $\beta_c = 0$ and $\partial L / \partial \tau$ bounded were valid. The chiroptical activities over this region are thus

correlated by

$$\frac{\frac{\partial}{\partial \tau} [Re(\kappa)]}{\frac{\partial}{\partial \tau} [Im(\kappa)]} \approx \frac{Re(L(\omega, 0))}{Im(L(\omega, 0))} := k(\omega) \quad (13)$$

Therefore, the magnification of chiral ORD effect, as shown in Section 2.1, implies that the CD measured would be amplified when detected using light source with wavelength far from chiral molecules' resonance.

2.3 | Full Wave Simulations

In this study, we performed numerical simulations using finite-element software COMSOL Multiphysics [30, 55]. An unit of the top silicon gratings were excited with a source port of TM and TE polarization separately, with perfectly matched layer (PML) applied in vertical boundaries. A range of duty cycle and thickness of the gratings were swept to determine the ideal parameters to convert CP light into elliptical polarization with high eccentricity. Similarly, the bottom aluminium gratings were designed to transmit two orthogonal polarization state at significant difference. Subsequently, gratings and chiral medium were simulated as a whole under injection of source port with CP state. The details of gratings' simulation setup and viable solutions were presented in Section S2.

Chiral material could be simulated by making three major changes to the underlying electromagnetic equations [55]: the

constitutive equations, weak expression, and applying surface current densities to boundaries of chiral medium and gratings system. The constitutive relations for $\vec{D}, \vec{H}, d\vec{H}/dt$ were rewritten according to Equation (9), assuming time evolution of $e^{i\omega t}$, with the relative permittivity ϵ_c and Pasteur parameter κ defined in Equation (10). The chiral medium wave equation was derived from applying constitutive Equation (9) to Maxwell equations, resulting in the weak form:

$$\text{WF} = - \left(\nabla \times \vec{E} \right) \cdot \left(\nabla \times \vec{T} \right) - 2\kappa\mu_o\omega \vec{T} \cdot \left(\nabla \times \vec{E} \right) + \mu_o\epsilon_o\epsilon_c\omega^2 \vec{T} \cdot \vec{E} \quad (14)$$

where $\vec{T}$ is the test function. Finally, according to the tangential continuity of magnetic field, surface current densities of

$$\vec{J}_s = i \vec{n} \times \left(\kappa \vec{E}_2 \right) \quad (15)$$

were applied to the boundaries between chiral medium and other components of the system. The details of setting up chiral medium and relevant derivations were discussed further in Section S3.

3 | Results and Discussion

3.1 | Simulation of Chiral Medium

The enantiopure medium shown in Figure 2 was simulated using the following parameters: $\epsilon_{c0} = 1.7732$, $\gamma_c = 8.5 \times 10^{-3}$ eV, $\omega_0 = 2\pi c/\lambda_0 = 2\pi c/(350 \text{ nm})$, $\Gamma_{12} = 0.2$ eV, $\beta_c = 1.825 \times 10^{-6}$ eV $\text{Cm}^{-2}\text{T}^{-1}$. These parameters were chosen such that the corresponding refractive index is approximately the reported refractive index of glucose solution with 20 g/L concentration [56]. The medium was defined as pure L-enantiomers due to stronger absorption of LCP light at resonance wavelength $\lambda_0 = 350$ nm (Figure 2A). Enantiomers response to CP light depended on its projection of magnetic dipole $\vec{\mu}_{12}$ onto electric dipole $\vec{m}_{12}$ being parallel or anti-parallel [57, 58]:

$$\beta_c \propto \vec{\mu}_{12} \cdot \vec{m}_{12} \quad (16)$$

Therefore, for a given molecule, a medium with enantiomeric ratios of ρ L-enantiomers and $(1 - \rho)$ D-enantiomers could be simulated by changing the coefficient associated to β_c :

$$\begin{aligned} \beta_c &\propto \rho * \left(\vec{\mu}_{12} \cdot \vec{m}_{12} \right) + (1 - \rho) * \left[- \left(\vec{\mu}_{12} \cdot \vec{m}_{12} \right) \right] \\ &= (2\rho - 1) * \left(\vec{\mu}_{12} \cdot \vec{m}_{12} \right) \end{aligned} \quad (17)$$

where $\rho = 0, 0.5, 1$ represented pure D-enantiomers, racemic mixture, and pure L-enantiomers configurations respectively (Figure 2B). CD was calculated using $(T_{LCP} - T_{RCP})/(T_{LCP} + T_{RCP})$. Molecules with different resonant frequencies could be simulated by changing the ω_0 (Figure 2C) and medium with different concentrations are simulated by multiplying γ_c and β_c with the same factors (Figure 2D). The CD of enantiospecific solution

whose molecules resonant wavelength lies in UV regime was very weak over in the subsequent detection wavelength region of 600 nm to 700 nm.

3.2 | Determination of Silicon Gratings Structural Parameters

The parameters of gratings in DTGCA system were shown in Figure 3A. For a given bottom gratings' period of p nm, the top silicon gratings' period was fixed at $\sqrt{2}p$ nm. The degrees of freedom in simulation were limited to construct a repeating unit cell of the overall double gratings system. The silicon gratings were covered in medium with background permittivity $\epsilon_{c0} = 1.7732$, and transmittance corresponding to parameter sweeps over its duty cycle and thickness were presented (Figure 3C–E). The gratings with chosen width of 66 nm (corresponding to duty cycle of 0.31) and thickness of 120 nm convert light of CP state with wavelength 632 nm into elliptical polarization state of eccentricity $e = 0.99992$, which could be treated as linearly polarized state (marked with asterisk in Figure 3C–E).

3.3 | Separation of T_{RCP} Over Different Enantiomeric Ratios

The transmission of 632 nm RCP light using the calculated gratings parameter and 350 nm resonant chiral molecules over different enantiomeric ratios were calculated and compared to transmission through chiral medium alone, as shown in Figure 4 (top graph). The separation factor from the baseline of racemic ratio was calculated using:

$$g = \left[\frac{T_{RCP}(\rho)}{T_{RCP}(0.5)} - 1 \right]_{st.} \left[\frac{T_{RCP}(\rho)}{T_{RCP}(0.5)} - 1 \right]_{wo}^{-1} \quad (18)$$

where subscript “st” and “wo” represent the transmission with and without the DTGCA system respectively, and the result were plotted in Figure 4A (bottom graph). The calculated separation factor g were above 200 over the order of magnitudes of measurement, implying it was easier to distinguish different enantiomeric ratios using the proposed DTGCA system. Meanwhile, we also analyzed the amplification capability of this structure when applied to pure right-handed glucose solutions with different concentrations. The results are shown in Figure 4B. It can be observed that this structure exhibits prominent amplification performance within the concentration range of 20 g/L to 200 g/L.

3.4 | Response to Different Chiral Analytes and Incident Polarization

We systematically quantified the separation factor g for chiral analytes whose molecules' resonant eigenfrequencies span the UV (250 – 450 nm) and NIR (800 – 1000 nm) regimes while keeping the detection wavelength fixed at 632 nm (Figure 5A). Despite the disparate native resonances, the proposed DTGCA enables amplification of separation factor uniformly over the same detection setup, underscoring its suitability for multi-analyte enantiomeric profiling without hardware reconfiguration.

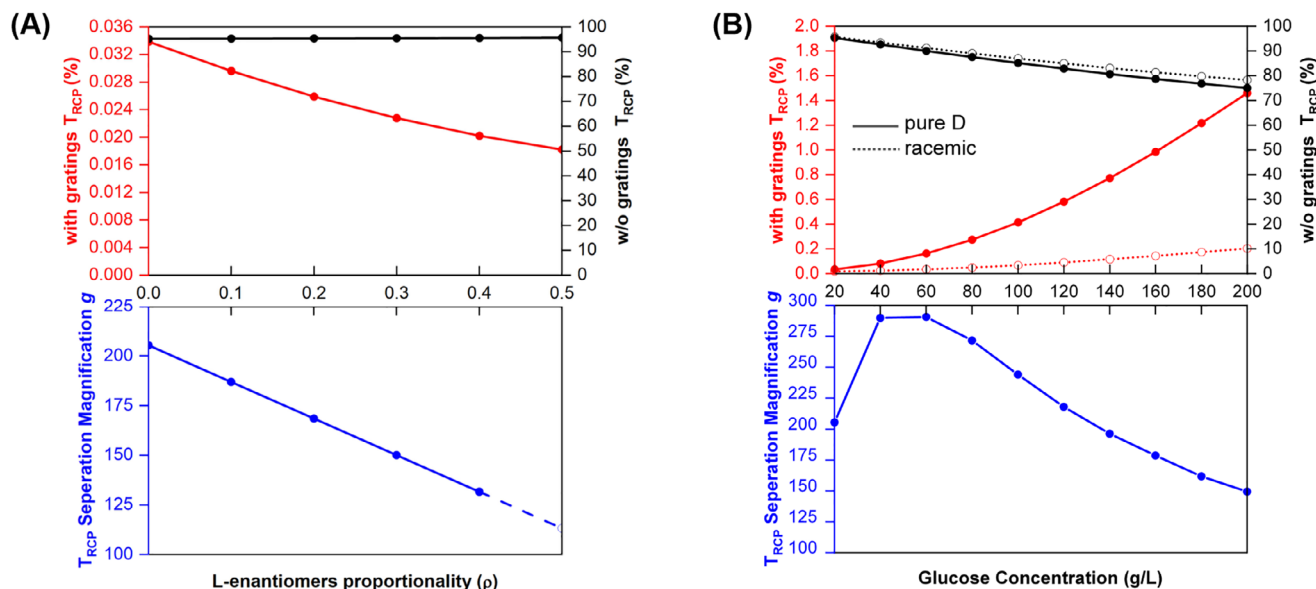


FIGURE 4 | (A) RCP light transmission at 632 nm for the enantiomeric series defined in Figure 2B. Top: RCP light transmission with (left axis) and without (right axis) the DTGCA system. Bottom: the corresponding separation factor g . The singularity at racemic proportionality were added using average of neighbouring g . (B) RCP light transmission and separation factor corresponding to different solution concentrations.

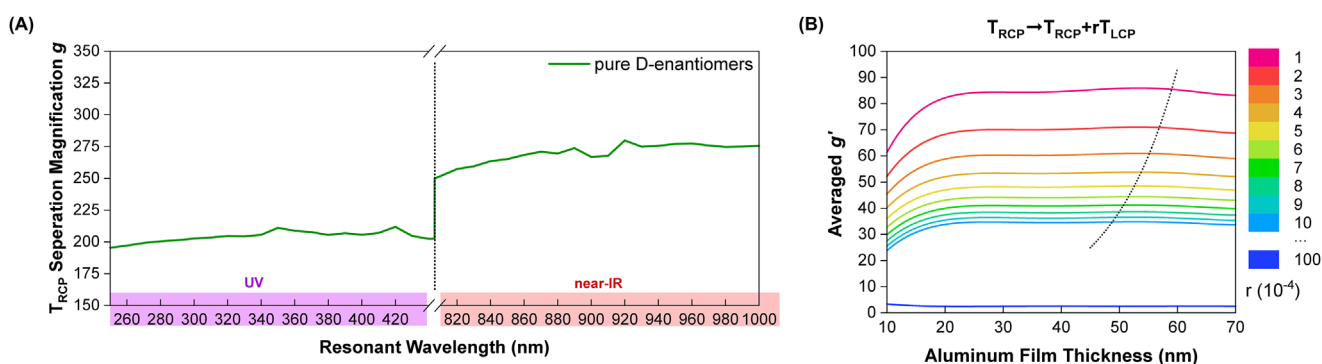


FIGURE 5 | (A) Separation factor g calculated at 632 nm wavelength for chiral medium with resonance wavelength in UV and near-IR regimes. (B) Averaged modified separation factor g' of non-zero r vs bottom gratings' aluminum film thickness. The black dotted line represents the film thickness corresponding to peak g' at different r .

Subsequent investigation on the incident source polarization state purity revealed that separation factor scales monotonically with bottom-grating Al thickness only when the source is a pure RCP state. Introducing even a minor LCP admixture breaks this monotonicity as the weak value amplification factor is sensitive to the relative Stokes vector orientation. Increasing the thickness of Al film of the bottom gratings further restrict the energy transmission and increases the separation factor at the same time. However, when the light source is superposed with a portion of LCP state, the separation factor is no longer monotonically related to Al film thickness. Assuming the intensity ratio of LCP to RCP state in incident light source is r , the separation factor is rewritten into

$$g' = \left[\frac{T_{RCP}(\rho) + rT_{LCP}(\rho)}{T_{RCP}(0.5) + rT_{LCP}(0.5)} - 1 \right]_{st.} \left[\frac{T_{RCP}(\rho) + rT_{LCP}(\rho)}{T_{RCP}(0.5) + rT_{LCP}(0.5)} - 1 \right]_{wo}^{-1} \quad (19)$$

The averaged g' over the same enantiomeric ratios discretization in Section 3.3 corresponding to different intensity ratio r

were calculated and fitted with polynomial curve, as shown in Figure 5B. The peak of averaged g' corresponding to non-zero r were shifted towards thinner Al film. Furthermore, the higher the intensity of opposite CP presented in incident source, the lower the magnitude of g' dropped to. In actual practice, the proposed DTGCA system is susceptible to the condition of incident source's polarization state, thus requiring an adjustment on design parameters such as metallic film thickness for the most optimal separation factor. In addition, the structure of our system exhibits significant advantages in integration capability. Although the system designed in this work adopts a two-layer twisted grating configuration, it imposes no requirements on the alignment registration between the horizontal positions of the two gratings. This implies that, for array integration of the system, we can first fabricate the double-layer grating structure and then divide it into arrays with arbitrary unit cell sizes. Therefore, combined with techniques such as microfluidics, the integration of the system can be

readily realized. Furthermore, the grating structures can be fabricated via approaches like holographic lithography, rather than point-by-point manufacturing methods such as electron-beam direct writing, which greatly improves the integration efficiency.

As benchmarked in Table S1 (see Section S1), compared to previous designs, our double-layer subwavelength gratings feature low fabrication complexity, making them highly compatible with standard microfabrication processes and scalable integration. Meanwhile, the structure achieves a competitive enhancement of 200 in normalized separation factor, outperforming most low-cost dielectric structures. Furthermore, the device supports both UV and NIR resonant responses in the visible spectrum, offering broader applicability than conventional single-band designs. Overall, our approach effectively addresses the trade-off between enhancement performance and fabrication complexity, providing a practical path toward high-performance, integrable chiral enhancement devices.

4 | Conclusions

In conclusion, we proposed the DTGCA system, consisting of two simple gratings structure, dielectric and bilayer metallic gratings. This system, compared to pioneering works, offers significant advantages in fabrication, miniaturization and integration. Using the principle of linear correlation between variation in ORD and CD in the off-resonant spectrum region, the DTGCA system achieves highly sensitive detection for various chiral molecules whose resonance wavelengths were far from detection wavelength, bypassing the requirement of responding frequencies matching and lowering the probability of inducing photodamage. This work shows great potential in asymmetric chemical synthesis, pharmaceuticals, and life science research. However, as analyzed above, our proposed system imposed high requirement on the purity of incident source's polarization state, posing challenges to the laser source system and the laboratory environment.

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Author Contributions

D.W., M.S., and X.L. conceived the idea and supervised the research. T.L. and S.H.T. performed theoretical description and device designs. S.H.T. and K.D. carried out the simulation of gratings and chiral medium. T.L. and Y.W. performed the separation factor and polarization state response calculation and analyzed the results and data. T.L., S.H.T., X.L., M.S., and D.W. wrote the paper. All the authors discussed the contents and prepared the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: adom71737-sup-0001-SuppMat.docx.