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CdF(C₆H₄NO₂)(H₂O): a UV nonlinear optical material with unprecedented SHG and birefringence *via* π -conjugated rings and a unique "Warren truss structure" †

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We report the design and synthesis of a novel ultraviolet (UV) nonlinear optical (NLO) material, CdF ($C_6H_4NO_2$)(H_2O), featuring a unique "Warren truss structure". This material exhibits a two-dimensional (2D) layered architecture structure composed of highly polarized [CdNO₂F₃] octahedra and π -conjugated organic rings ($C_6H_4NO_2$)⁻. Notably, CdF($C_6H_4NO_2$)(H_2O) demonstrates exceptional second-harmonic generation (SHG) response, with an intensity 3.2 times that of KH₂PO₄ (KDP), and a large birefringence of 0.26@546 nm, which is highly unusual for UV fluorides with a bandgap of >4.2 eV. Theoretical calculations and structural analysis reveal that the introduction of ($C_6H_4NO_2$)⁻ into CdF₂ induces significant structural distortion and polarization, leading to the formation of a non-centrosymmetric "Warren truss structure". This structure aligns [CdNO₂F₃] octahedra and organic rings in a highly ordered manner, which is crucial for the enhanced SHG and large birefringence. Our findings provide a new strategy for designing high-performance UV NLO materials by leveraging organic—inorganic hybrid structures.

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Introduction

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The rapid advancement of quantum technology (QT) is revolutionizing the capabilities of communication multiplexing and high-dimensional quantum information processing, with significant implications for spin-orbit angular momentum photonics. In this context, materials with strong second-harmonic generation (SHG) effects and high birefringence are urgently needed to enhance quantum optical techniques, particularly for efficient frequency doubling and precise manipulation of photons carrying orbital angular momentum (OAM).¹⁻³ However, the development of such materials is hindered by the contrasting microstructural requirements for SHG and birefringence, making it challenging to meet both criteria simultaneously. This is especially true in the ultraviolet (UV)

Fluorine, often referred to as the "star element" in nonlinear optical (NLO) materials, is known for its highest electronegativity, which significantly influences crystal structure regulation and optical bandgap enhancement.4 Its incorporation optimizes birefringence and reduces refractive index dispersion, thereby enabling shorter phase-matching wavelengths.5 Over the past decade, more than 200 fluorides and their derivatives have been reported, playing a crucial role in optoelectronic applications. However, despite their potential, these materials often fail to combine a large bandgap (>4.2 eV), strong SHG (>3 times KDP), and high birefringence (>0.2).6-23 Pure metal fluorides, while gaining attention as UV NLO materials, are similarly limited by weak SHG and small birefringence.^{24,25} These limitations have significantly restricted the application of fluorides and their derivatives in quantum optical technologies.

Recently, planar conjugated organic rings have garnered significant attention due to their remarkable enhancement of SHG and birefringence. For example, organic groups such as $(H_2C_6N_9)^-$, $(C_7H_4NO_4)^+$, $(C_3N_6H_7)^+$, and $(C_3N_2H_5)^+$ exhibit high optical activity and have been used to construct large birefringent crystals. Similarly, groups like $(C_3N_3O_3)^{3-}$, $(C_5H_6NO)^+$, $(HC_3N_3S_3)$, and $(H_2C_6N_7O_3)^-$ have been identified as excellent NLO active units. These findings suggest that

band, where materials with a bandgap of >4.2 eV are required, but few exhibit both strong SHG and large birefringence.

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incorporating metal fluorides into organic rings could be an effective strategy to enhance SHG and birefringence. However, this approach remains largely unexplored, particularly for UVtransmitting materials with strong SHG and birefringence.

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Metal fluoride CdF2, despite its potential as a UV NLO material, lacks SHG due to its centrosymmetric structure, and its calculated birefringence (0.00002@546.1 nm) is negligible. Here, we report the synthesis of a novel metal-organic complex, $CdF(C_6H_4NO_2)(H_2O)$, by introducing π-conjugated organic ring (C₆H₄NO₂)⁻ into CdF₂. This substitution not only breaks the centrosymmetry but also induces significant polarization anisotropy and second-order hyperpolarizability. Compared to the centrosymmetric CdF₂ (SHG = 0, negligible birefringence of 0.00002@546 nm), the resulting $CdF(C_6H_4NO_2)(H_2O)$, compound, exhibits remarkably enhanced SHG (3.2×KDP) and birefringence (0.26@546 nm), while maintaining UV transmittance (band gap = 4.41 eV). This material represents a rare example of UV metal fluoride combining strong SHG and high birefringence. Our comprehensive study, including design, synthesis, structural analysis, properties, and theoretical calculations, reveals how the π-conjugated organic ring (C₆H₄NO₂) constructs a "Warren truss structure" in semi-organic metal fluorides. This unique structure aligns highly polarized [CdNO₂F₃] octahedra, leading to the observed strong SHG and large birefringence. Our findings not only advance the understanding of SHG and birefringence enhancement in metal fluorides but also highlight the potential applications of CdF(C₆H₄NO₂)(H₂O) in quantum optical technologies.

Results and discussion

The design idea of CdF(C₆H₄NO₂)(H₂O) is mainly based on the use of $(C_6H_4NO_2)^-$ with a planar π -conjugated organic ring to replace F in the simple metal fluoride CdF₂. CdF(C₆H₄NO₂) (H2O) is obtained using a hydrothermal method as detailed in the ESI.† As shown in Scheme 1, during the reaction process, since CdF2 is a strong base and weak acid salt, the entire reac-

$$CdF_2 + C_7H_7NO_2 \xrightarrow{H_2O} Cd(C_6H_4NO_2)(H_2O) + CH_3OH + HF$$

$$OCH_3 \qquad OH$$

$$S1 \qquad OH$$

$$CdF_2 \qquad OH$$

$$CdF_2 \qquad OH$$

$$CdF_2 \qquad OH$$

Scheme 1 Synthesis and mechanism of CdF(C₆H₄NO₂)(H₂O).

tion system is acidic. Initially, the raw material methyl nicotinate (S1) hydrolyzes to form nicotinic acid (S2) and methanol. Then, S2 reacts with F to produce S3 and the weak acid HF, thereby exposing two coordination active sites of N and O. Subsequently, S3, F⁻, and H₂O coordinate with Cd²⁺ to form $CdF(C_6H_4NO_2)(H_2O)$.

Fig. 1a and b illustrate the structural transformation from the precursor CdF₂ to the product CdF(C₆H₄NO₂)(H₂O). The introduction of the organic ring (C₆H₄NO₂) disrupts the interconnected $[(Cd_2F_2)^{2+}]_{\infty}$ chains, forming a unique structure resembling a "Warren truss bridge" within the two-dimensional plane. The rigid organic ring (C₆H₄NO₂) acts as the "diagonal" of the bridge, connecting to Cd through coordination atoms at both ends, thereby forming a stable triangular structure that supports the "top/bottom chord" of the bridge, namely the $[(Cd_2F_2)^{2+}]_{\infty}$ chains, aligning them in a completely parallel and consistent arrangement. The addition of (C₆H₄NO₂)⁻ transforms the cubic [CdF₈] in CdF₂ into a distorted octahedron [CdNO₂F₃], resulting in structural symmetry breaking from a centrosymmetric to a non-centrosymmetric structure.

CdF(C₆H₄NO₂)(H₂O) crystallizes in the polar space group $P2_1$ with unit cell parameters of a = 9.2128 Å, b = 4.2589 Å, c =10.740 Å, $\alpha = \gamma = 90^{\circ}$, $\beta = 114.506(4)^{\circ}$, and V = 383.44(10) Å³ (detailed information is provided in Table S1†). Its CCDC number is 2419363.† The metal Cd is coordinated with one N and one O from two organic rings $(C_6H_4NO_2)^-$, one water molecule, and three F ions, forming a distorted [CdNO₂F₃] octahedron. The bond lengths of Cd-N, Cd-O, and Cd-F are 2.302 Å, 2.216–2.303 Å, and 2.195–2.311 Å, respectively, which are consistent with previously reported literature (Fig. 2a). 34 As shown in Fig. 2b, the [CdNO₂F₃] octahedra with two orientations are alternately arranged along the b-axis, forming a zigzag one-dimensional chain. These chains are interconnected by the organic rings (C₆H₄NO₂)⁻ (the distance between two chains is 9.2128 Å, and the angle of the organic ring is 59.2°, as shown in Fig. S1†), creating a unique structure resembling a "Warren truss bridge". They extend infinitely along the ab plane to form a two-dimensional layer. Subsequently, these two-dimensional layers are closely stacked along the c-axis in the same orientation, ultimately forming the unique spatial structure of CdF(C₆H₄NO₂)(H₂O) (Fig. 2c and d).

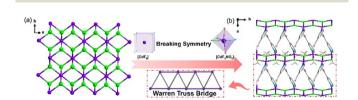
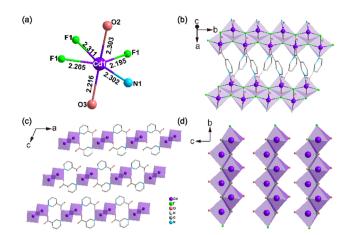


Fig. 1 Transition from a centrally symmetrical CdF₂ structure (a) to a NCS structure of $CdF(C_6H_4NO_2)(H_2O)$ (b). The upper part of the red arrow indicates the evolution of the cube [CdF₈] to the twisted octahedron [CdNO₂F₃]. Below the red arrow, a comparison of the CdF (C₆H₄NO₂)(H₂O) structure with the Warren truss bridge is shown.



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Fig. 2 (a) The coordination environment of Cd; (b) the two-dimensional layered structure of CdF(C₆H₄NO₂)(H₂O) in space; (c) the structure of $CdF(C_6H_4NO_2)(H_2O)$ in the ac plane; (d) the structure of $CdF(C_6H_4NO_2)$ (H_2O) in the bc plane.

XPS spectral analysis of CdF(C₆H₄NO₂)(H₂O) (Fig. 3a, b and S6, S7†) confirms Cd's oxidation state as Cd²⁺ with peaks at 404.65 eV and 412.62 eV in the 402-414 eV binding energy range and F's oxidation state as -1, consistent with the results of BVS calculations (Table S2†) and single-crystal structure resolution. The band gap of CdF(C₆H₄NO₂)(H₂O) is 4.41 eV, measured using the Kubelka-Munk method (Fig. 3c), 35 exceeding the 4.2 eV threshold for UV NLO materials and surpassing reported values for Na₂CeF₆ (3.89 eV),³⁶ KBi₄F₁₃ (4.24 eV),³⁷ and K₂SbF₂Cl₃ (4.01 eV), 38 indicating its UV application potential. IR absorption peaks align with single-crystal test results (Fig. S3†), and thermogravimetric tests show stability up to 150 °C (Fig. S4†).

The Kurtz-Perry method was used to measure³⁹ the SHG response of CdF(C₆H₄NO₂)(H₂O) under 1064 nm laser irradiation. Its SHG intensity increases with particle size, plateaus at 280-450 µm, and shows phase matching behavior. Within this size range, its SHG intensity is about 3.2×KDP (Fig. 3d and e). Generally, metal fluorides have weak NLO effects due to fluorine's weak deformability. For instance, the responses of KNa₂ZrF₇ (0.35×KDP),⁴ CsNaTaF₇ (0.20×KDP),⁴⁰ BaMgF₄ (0.085×KDP),⁴¹ BaZnF₄ (0.16×KDP),⁴² Na_2SbF_5 (0.17×KDP), ⁴³ and Na_2CeF_6 (2.1×KDP)³⁶ are all less than 1×KDP. Although Na₂CeF₆ has a rare 2.1×KDP SHG response, its 3.89 eV optical band gap limits its UV band application. Fig. 3f shows the comparison of the optical band gaps and SHG effects of recent metal fluorides (Table S8†), showing that CdF(C₆H₄NO₂)(H₂O)'s SHG effect is the strongest among those of recent UV NLO metal fluorides with a band gap of >4.2 eV. Further dipole moment analysis reveals a calculated dipole moment of 6.14 D for CdF(C₆H₄NO₂)(H₂O), aligning with its SHG intensity.

The second harmonic generation (SHG) effect is generally diminished in fluorides with short absorption edges. The origin of the nonlinear optical (NLO) efficiency is predominantly contingent on the asymmetry and arrangement of the polyhedra within the crystal structure. In the compound CdF (C₆H₄NO₂)(H₂O), the severely distorted octahedra [CdNO₂F₃] constitute a one-dimensional sawtooth chain. Subsequently, these chains are interconnected by the organic ring

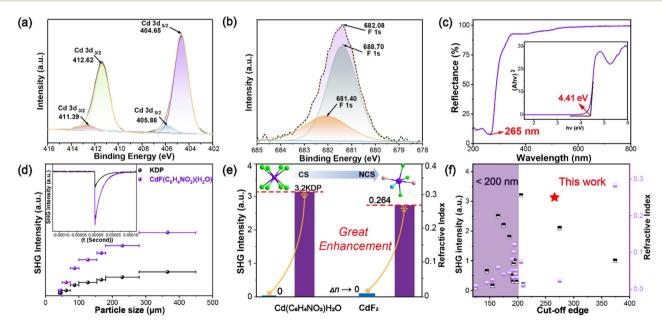


Fig. 3 (a) XPS spectrum of Cd-3d in CdF($C_6H_4NO_2$)(H_2O). (b) XPS spectrum of F-1s in CdF($C_6H_4NO_2$)(H_2O). (c) UV spectrum of CdF($C_6H_4NO_2$)(H_2O). (d) The particle size of CdF(C₆H₄NO₂)(H₂O) and KDP as a function of the SHG response. The inset is a SHG intensity signal plot of CdF(C₆H₄NO₂) (H₂O) with KDP in the particle size range of 280–450 μm. (e) Comparison of SHG response and birefringence performance of CdF(C₆H₄NO₂)(H₂O) and CdF₂. (f) Scatter plots of bandgap, birefringence and SHG intensities of CdF($C_6H_4NO_2$)(H₂O) versus various fluorides. (Black on the left indicates SHG, purple on the right represents birefringence, and black at the bottom denotes the cut-off edge.)

(C₆H₄NO₂)⁻, culminating in a distinctive "Warren truss bridge" structure. This unique configuration facilitates the optimal alignment of the [CdNO₂F₃] octahedra and (C₆H₄NO₂) within the crystal lattice, which is the pivotal factor enabling the large SHG and high birefringence of CdF (C₆H₄NO₂)(H₂O). These structural analyses offer invaluable insights into the design of NLO materials with enhanced SHG effects, potentially guiding future research endeavors in this domain.

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The birefringence of CdF(C₆H₄NO₂)(H₂O) single crystals, measured using a polarizing microscope (Fig. 4a), was found to be 0.253@546.1 nm for a crystal thickness of 7 µm (Fig. 4bd). This value exceeds those of commercial birefringent cryssuch as MgF₂ (0.012@589.3 nm),⁴⁴ (0.122@532 nm),45 and CaCO3 (0.172@589 nm)46 and represents the upper limit of UV pure metal fluorides and semi-S8†), organometallic fluorides (Table $(H_2DpA)_2SiF_6(0.282)$. ⁴⁷ $(H_2DpA)_2SiF_6$ has only 1×KDP and a band gap of 2.84 eV, significantly lower than the required 4.2 eV and 3×KDP. The calculated linear optical properties (Fig. 4e) reveal strong anisotropy with refractive indices n_z = 1.764, n_x = 1.745, and n_y = 1.511, yielding birefringence Δn = 0.264@546 nm, agreeing well with the measured value. Additionally, the birefringence of CdF2 at 546 nm was calculated to be 0.00002 (Fig. 4f), which is nearly 10 000 times lower than that of CdF(C₆H₄NO₂)(H₂O).

First-principles density-functional theory calculations (Fig. S8-S11†) reveal that CdF(C₆H₄NO₂)(H₂O) and CdF₂ have indirect band gaps of 3.507 and 3.743 eV, respectively. The density of states diagram (Fig. S11†) shows that the valence band top is dominated by O-2p orbitals with minor F-2p contributions, while the conduction band bottom is influenced by C-2p, N-2p, and O-2p orbitals. This indicates that the band gap of CdF(C₆H₄NO₂)(H₂O) is primarily determined by the (C₆H₄NO₂) unit, with minimal contribution from Cd-F interactions (Fig. 5b).

Quantum chemistry-based frontier orbital calculations on CdF(C₆H₄NO₂)(H₂O) primitives reveal the contributions of $[CdNO_2F_3]$ and $(C_6H_4NO_2)^-$ units. In $CdF(C_6H_4NO_2)(H_2O)$, the HOMO is dominated by F-2p and Cd-4d orbitals, while the LUMO is primarily influenced by the $(C_6H_4NO_2)^-$ unit and Cd and F orbitals within the [CdNO₂F₃] octahedron (Fig. S12 and S13†). These d-p hybridization events facilitate electron movement, under the photoelectric field, enhancing the second-harmonic generation (SHG) effect.

Under Kleinman symmetry constraints, 48 CdF(C₆H₄NO₂) (H_2O) exhibits four independent nonzero SHG coefficients: d_{14} = -0.241 pm V^{-1} , $d_{16} = 1.114 \text{ pm V}^{-1}$, $d_{22} = 0.747 \text{ pm V}^{-1}$, and $d_{23} = -0.439 \text{ pm V}^{-1}$, with d_{16} being the largest and consistent with experimental results. Further investigation through SHGweighted density maps (Fig. 5a, b and S14, S15†) shows that the occupied states in the virtual electron (VE) and virtual hole

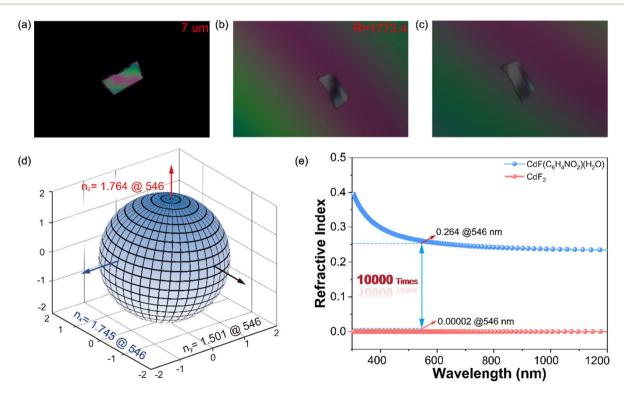


Fig. 4 (a) Thickness of selected wafers measured using the birefringence of $CdF(C_6H_4NO_2)(H_2O)$. (b and c) $CdF(C_6H_4NO_2)(H_2O)$ extinguished under cross-polarized light. (d) Theoretically calculated refractive index of CdF(C₆H₄NO₂)(H₂O). (e) Comparison of birefringence@546 nm between CdF₂ and $CdF(C_6H_4NO_2)(H_2O)$.

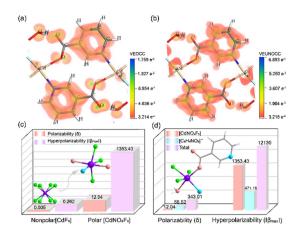


Fig. 5 SHG-weighted densities of the occupied (a) and unoccupied (b) states of CdF(C₆H₄NO₂)(H₂O) in the virtual electron process. (c) Hyperpolarizability and polarization anisotropy calculations for the nonpolar octahedron $[CdF_8]$ and the polar octahedron $[CdNO_2F_3]$. (d) Theoretical calculation of anisotropy and hyperpolarizability contributions of CdF($C_6H_4NO_2$)(H_2O), [CdNO₂F₃] and ($C_6H_4NO_2$)⁻.

(VH) processes are mainly from C-2p, N-2p, O-2p, and F-2p orbitals, while the unoccupied states are primarily from C-2p, N-2p, and Cd-4d orbitals. These findings confirm that the SHG density arises from the synergistic contributions of the $(C_6H_4NO_2)^-$ unit, F, and Cd atoms.

It is well known that anisotropy and hyperpolarizability are key parameters affecting second harmonic generation (SHG) and birefringence, respectively. We calculated these properties for $[CdF_8]$, $[CdNO_2F_3]$, $CdF(C_6H_4NO_2)(H_2O)$, and $(C_6H_4NO_2)$ using the LanL2DZ basis set in Gaussian⁴⁹ (Fig. 5c and d). For CdF₂, [CdF₈] shows near-zero hyperpolarizability and anisotropy, consistent with its poor birefringence and lack of SHG. In contrast, [CdNO₂F₃] in CdF(C₆H₄NO₂)(H₂O) exhibits hyperpolarizability and anisotropy values over 2000 and 5000 times higher than those of [CdF₈], highlighting its crucial role in enhancing optical properties (Fig. 5c). Fig. 5d shows that (C₆H₄NO₂)⁻ significantly contributes to birefringence, while the highly polarized [CdNO₂F₃] units drive strong SHG. Taken together, it is confirmed that the unique "Warren truss structure" formed by the π-conjugated organic ring (C₆H₄NO₂) leads to highly polarized and well-aligned [CdNO₂F₃] octahedra and (C₆H₄NO₂)-, which is the key factor leading to the strong SHG and birefringence of CdF(C₆H₄NO₂)(H₂O).

Conclusion

In summary, we have successfully synthesized $CdF(C_6H_4NO_2)$ (H2O), a novel UV NLO material with a unique "Warren truss structure". Compared to CdF2, which exhibits zero SHG effect and extremely low birefringence (0.00002@546 nm), CdF (C₆H₄NO₂)(H₂O) demonstrates remarkable enhancements in both properties, achieving a large SHG response (3.2×KDP) and high birefringence (0.26@546 nm). These striking improvements are attributed to the introduction of the π -conjugated organic ring $(C_6H_4NO_2)^-$, which leads to the formation of a highly polarized and well aligned [CdNO₂F₃] octahedra. Notably, this is the first UV fluoride material to simultaneously exhibit a large band gap (>4.2 eV), strong SHG effect (>3×KDP), and high birefringence (>0.2), making it a promising candidate for quantum optical technologies. Our study provides valuable insights into the design of non-centrosymmetric optoelectronic materials by constructing novel structures that activate high polarization and enhance optical properties.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

The authors declare no competing financial interest.

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