

BIC-stimulated tunable second-harmonic generation in transition metal dichalcogenide film coupled with high-quality dielectric metasurface

Alena A. Nazarenko, Alexander I. Musorin, Boris S. Luk'yanchuk and Andrey A. Fedyanin

Citation: Nazarenko AA, Musorin AI, Luk'yanchuk BS, et al. BIC-stimulated tunable second-harmonic generation in transition metal dichalcogenide film coupled with high-quality dielectric metasurface. *Opto-Electronics Plus* **1**, 250003(2025).

Received: 13 June 2025; Accepted: 28 July 2025; Published online: 31 July 2025

Related articles

Dual bound states in the continuum enhanced second harmonic generation with transition metal dichalcogenides monolayer

Peilong Hong, Lei Xu, Mohsen Rahmani

Opto-Electronic Advances 2022, **5**(7): 200097 doi: [10.29026/oea.2022.200097](https://doi.org/10.29026/oea.2022.200097)

Resonantly enhanced second- and third-harmonic generation in dielectric nonlinear metasurfaces

Ji Tong Wang, Pavel Tonkaev, Kirill Koshelev, Fangxing Lai, Sergey Kruk, Qinghai Song, Yuri Kivshar, Nicolae C. Panoiu

Opto-Electronic Advances 2024, **7**(5): 230186 doi: [10.29026/oea.2024.230186](https://doi.org/10.29026/oea.2024.230186)

Light-matter interaction in strong coupling regime based on bound states in the continuum

Peijuan Dai, Hetan Chen, Wei Wang

Opto-Electronics Plus 2025, **1**(1): 250005 doi: [10.29026/oea.2025.250005](https://doi.org/10.29026/oea.2025.250005)

High-Q resonances governed by the quasi-bound states in the continuum in all-dielectric metasurfaces

Cizhe Fang, Qiyu Yang, Qingchen Yuan, Xuetao Gan, Jianlin Zhao, Yao Shao, Yan Liu, Genquan Han, Yue Hao

Opto-Electronic Advances 2021, **4**(6): 200030 doi: [10.29026/oea.2021.200030](https://doi.org/10.29026/oea.2021.200030)

More related articles in Opto-Electronic Journals Group website 



BIC-stimulated tunable second-harmonic generation in transition metal dichalcogenide film coupled with high-quality dielectric metasurface

Alena A. Nazarenko^{1,2}, Alexander I. Musorin^{1,2}, Boris S. Luk'yanchuk² and Andrey A. Fedyanin^{2*}

Abstract: Atomically thin films of transition metal dichalcogenides (TMDCs) are a promising class of novel materials that can contribute to the development of new information processing methods in optoelectronics and photonics. However, the functionalities of TMDCs monolayers for nonlinear-optical applications are limited by the atomic length of the light-matter interaction. Marrying these monolayers with resonant dielectric metasurfaces enables higher efficiencies of nonlinear processes, thereby circumventing the aforementioned drawback. This paper demonstrates the amplification of second-harmonic generation efficiency up to 3 orders of magnitude attributed to quasi-bound state in the continuum (quasi-BIC). The enhancement occurs during the gradual spectral tuning of the quasi-BIC state, excited in a metasurface made of titanium dioxide nanodisks, until its spectral position coincides with a solitary bright exciton of a molybdenum diselenide monolayer. This spectral overlap is achieved by varying the angle of incidence of incoming radiation.

Keywords: nonlinear optics; second-harmonic generation; transition metal dichalcogenides; bound states in the continuum; dielectric metasurfaces

Introduction

The growing interest in two-dimensional films of transition metal dichalcogenides (TMDCs) is related to their tunable optical and electrical properties, which open up new possibilities for their applications in optoelectronics and photonics¹. TMDC monolayers form an X-M-X lattice with atomic layers being weakly bonded to each other by means of van der Waals coupling. An array of transition metal atoms, M, is located between two arrays of chalcogen atoms, X. Molybdenum, tungsten or chromium are often used as transition metal atoms, while sulfur, selenium or tellurium play the role of chalcogen atoms. Monolayers of transition metal dichalcogenides exhibit a direct band gap², strong two-dimensional electron confinement and reduced dielectric screening, leading to the formation of exciton states at room temperature^{3,4}. The broken inversion symmetry in TMDC monolayers results in notably high values of second-order nonlinear susceptibility^{5–7}, establishing them as highly suitable candidates for optical second-harmonic

generation (SHG) applications.

The efficiency of nonlinear-optical effects in TMDC films can be significantly increased by coupling them with resonant metasurfaces^{8–13}. Metasurfaces provide a pathway to metadevices that enable comprehensive control over light parameters^{14,15}. Since plasmonic metasurfaces have large ohmic losses, the current research is focused on high-index dielectric metasurfaces, the optical losses of which are primarily determined by emission^{16–20}. The presence of Mie resonances in dielectric metasurfaces results in the enhancement of local fields, which in turn boosts the efficiency of harmonic generation^{9,21–23}.

In this paper, we demonstrate the amplification of the nonlinear signal in the TMDC monolayer due to the integration of the film with a metasurface that supports high-quality bound state in the continuum (BIC) resonance. We propose a way to maximize the nonlinear signal by adjusting the spectral position of the metasurface resonance through varying the angle of incidence (AOI) of the fundamental radiation. This approach enables us to minimize the

Received: 13 June 2025

Accepted: 28 July 2025

Published online: 31 July 2025

¹Department of Materials Science, Shenzhen MSU-BIT University, Shenzhen 517182, China; ²Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia.

*Correspondence: A A Fedyanin, E-mail: fedyanin@nanolab.phys.msu.ru.

distortion of the resonance wavelength caused by inaccuracies and deviations in the manufacturing process and simultaneously increase the overlap integral with excitons of the TMDC film maximizing the SHG efficiency.

Results and discussions

Optical spectroscopy

The metasurface under study is a square array of TiO₂ nanodisks on a transparent fused silica substrate (see Fig. 1(a)). The radius of the disks is $r = 185$ nm, the disks' height is $h = 120$ nm, the period of the structure is $p = 410$ nm. Molybdenum diselenide monolayer is chosen as a transition metal dichalcogenide, as it exhibits exciton resonant feature in the spectral range of Ti: Sapp laser generation, which is widely used in optical experiments due to wavelength tunability, operation stability and appropriate intensities. The MoSe₂ monolayer is characterized by a Lorentzian second-order nonlinear susceptibility spectral profile with an extremum around 800 nm⁷ (see Fig. 1(b)). The thickness of the monolayer equals to 0.75 nm ($h_{\text{flake}} = 0.75$ nm). The dispersion of the complex refractive index is consistent with the literature²⁴ and presented in Fig. 1(b). The large absolute value of the imaginary part of the MoSe₂ refractive index ~ 0.5 in the studied spectral range does not significantly affect the transmission coefficient due to the small thickness of the film. The mentioned above parameters of the metasurface induce a quasi-BIC resonance in the vicinity of MoSe₂ nonlinear susceptibility resonance, as will be shown later.

The metasurface is irradiated with s-polarized light with intensity of $I_0 = 1$ GW/cm², which is a typical value for nonlinear optical experiments²¹ and below the laser-induced damage threshold of MoSe₂⁷. The amplitude of the incident electric field can be estimated as $E_0 = \sqrt{2I_0 \sqrt{\mu_0/\varepsilon_0}} \approx 8.7 \times 10^7$ V/m and the magnetic field

$H_0 = E_0 \sqrt{\varepsilon_0/\mu_0} \approx 2.3 \times 10^5$ A/m, where ε_0 , μ_0 are vacuum permittivity and vacuum permeability, respectively. The power of the incident radiation in this case will be fairly estimated as $W_0 = I_0 p^2 \approx 1.7$ W, where p^2 is the cell area with a period of p . The calculations are carried out using the finite element method in COMSOL Multiphysics software and are described in detail in the Supplementary materials.

Figure 2(a) shows the transmittance spectra of the sample at several AOIs. The calculations were performed in the wavelength range from 700 nm to 850 nm, which includes the spectral area around the maximum of nonlinear susceptibility of the film and displays the positions of the quasi-BIC resonance in the case of oblique incidence of light. The transmittance spectrum for normal incidence has no resonant features, which, however, emerge at oblique incidence (see Fig. 2(a)). For instance, a high-quality resonance is observed at the wavelength of 712 nm at AOI = 1° (cyan curve in Fig. 2(a)) and shifts to 730 nm at AOI = 10°. This behavior is typical for quasi-bound states in the continuum²⁵. BIC modes do not vanish with system parameters variation, which allows to characterize them by topological invariants, or topological charges. For the further check of the excited in the TiO₂ metasurface resonance we evaluate a topological charge q according to the formulae:

$q = \frac{1}{2\pi} \oint_C d\mathbf{k} \cdot \nabla_{\mathbf{k}} \phi(\mathbf{k})$ ^{25,26}. Here, $\phi(\mathbf{k})$ is the angle of polarization vector and C is a closed circular path in momentum space that goes around the studied mode in the counterclockwise direction. According to our calculations, described in detail in the Supplementary materials, the topological charge of the studied system is equal to +1, which proves the existence of the quasi-BIC resonance in our system.

This high-quality resonance is the overlapped magnetic dipole (MD, orange curve) and magnetic quadrupole (MQ, violet curve) modes according to the multipole decomposition^{27,28} shown in the Fig. 2(b). The minor contributions

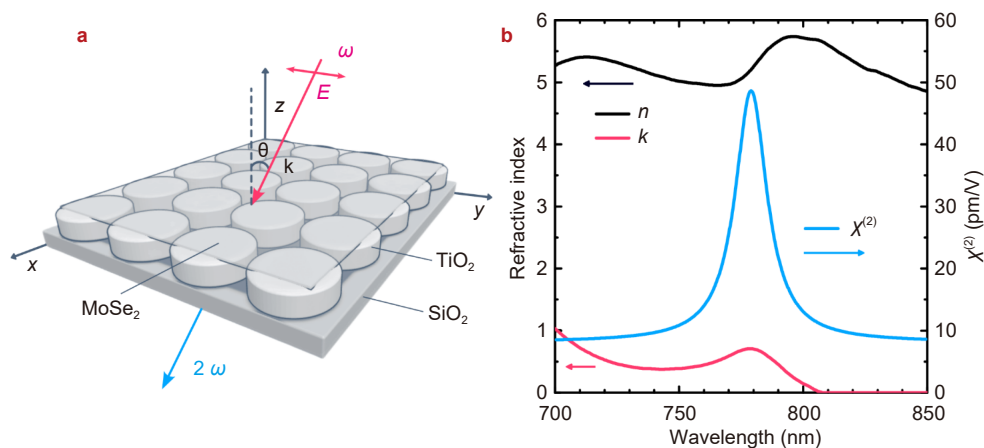


Fig. 1 | (a) Schematic illustration of the sample; (b) spectra of the real (n , black curve) and imaginary (k , red curve) parts of the refractive index of the MoSe₂ monolayer²⁴ and the spectrum of the second-order nonlinear susceptibility ($\chi^{(2)}$, blue curve).

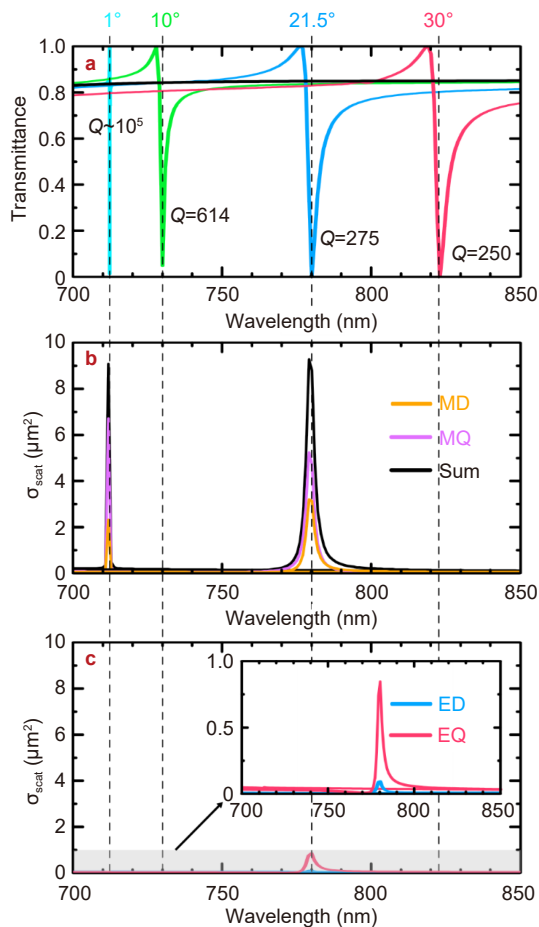


Fig. 2 | (a) Transmittance spectra at various AOI: 0° (black curve), 1° (cyan curve), 10° (green curve), 21.5° (blue curve), 30° (red curve), (b) MD, MQ modes and (c) ED, EQ modes of the multipole decomposition at 1° and 21.5° (the inset demonstrates the same spectra on a different scale).

from electric modes are displayed in the Fig. 2(c).

Estimations of the field amplitude enhancement are carried out for the wavelength of 712 nm at AOI = 1° (see Fig. 3). Figure 3 illustrate the electric field distribution normalized by E_0 and Figure 3 are the magnetic field distributions normalized by H_0 , where E_0 and H_0 are electric and magnetic field amplitudes of the incident field. The strong field localization due to the presence of quasi-BIC resonance is observed inside the disk at the middle of its height. The field amplification is equal to 180 for the electric field and to 590 for the magnetic field. At the top of the disk, where the nonlinear material is supposed to be located, the amplification reaches 120 for the electric field and 400 for the magnetic field (see Fig. 3(c-f)), that is sufficient to observe second-harmonic (SH) signal enhancement.

The quasi-BIC resonance aligns spectrally with the peak of the nonlinear susceptibility of the MoSe₂ monolayer at the AOI of 21.5° and the wavelength of 779 nm (see Figs. 1(b) and 2(a)). A further increase in the angle of incidence up to 30° leads to the red shift of the BIC resonance to 822 nm. The resonances have high quality factors (Q-factors) with transmittance dropping almost to zero. The asymmet-

ric Fano type lineshape of the resonances prompts the calculation of Q-factor values using the Fano formula²⁹, which gives the following results: $Q_1 = 6 \times 10^4$ for AOI = 1°, $Q_{10} = 614$ for 10°, $Q_{21.5} = 275$ for 21.5° and $Q_{30} = 250$ for 30°. An increase of the Q-factor value with decreasing asymmetry of the system is another indication that the resonance is a quasi-bound state in the continuum. Such modes have been observed previously in similar nanodisk arrays^{30,31}. This increase in the Q-factor is accompanied by growing local field values: 19 and 25 for the electric and magnetic fields respectively at the AOI = 30°, 20 and 31 at 21.5°, 22 and 63 at 10° and the aforementioned values 180 and 590 at 1°.

Nonlinear-optical spectroscopy

This section describes the influence of varying Q-factors and the overlap of resonances on the SHG process. The source of the nonlinear signal is MoSe₂ monolayer placed on top of the metasurface, where the local field enhancement is 120 at AOI = 1° for the wavelength 712 nm. The high values of local fields in the area of nonlinear material allow for the significant values of nonlinear polarization according to the formula $P^{NL}(2\omega) = \chi^{(2)}(\omega) E(\omega) E(\omega)$. This value can be further increased at the exciton-induced maximum of $\chi^{(2)}(\omega)$ of the TMDC monolayer. Thus, the considerable values of SHG are expected to be observed in the case of the spectral overlap of the quasi-BIC and exciton resonances. The monolayer thickness is taken to be $h_{\text{flake}} = 0.75$ nm and dispersion of the complex refractive index corresponds to literature²⁴ (see Fig. 1(b)). Calculations of the nonlinear response of such hybrid metasurface are also carried out using the finite element method in COMSOL Multiphysics software by setting the surface current density of the film, as described in detail in the Supplementary materials.

Figure 4(a) shows the second-harmonic (SH) spectra for five angles of incidence of s-polarized light in a logarithmic scale: 0° (black curve), 1° (cyan curve), 10° (green curve), 21.5° (blue curve) and 30° (red curve). The only resonant feature at normal incidence is associated with the bright exciton state in the monolayer at the wavelength of 779 nm. The SH signal at this fundamental wavelength reaches 6×10^{-10} W. This value is similar in order of magnitude to the response of the film placed on top of an unstructured layer of TiO₂ of the same thickness of $h = 120$ nm. The maximum of the SH signal in this structure is 1×10^{-10} W (calculations are not presented).

Two resonances are observed in second-harmonic spectra at AOI = 1° and 10° (see Fig. 4(a)). The nature of the left one is the quasi-BIC resonance of the metasurface, while the right one is the material resonance of the two-dimensional TMDC film at 779 nm. The SH signal power for 1° is 2×10^{-8} W at the wavelength of the structural resonance (712 nm) and 6×10^{-10} W at the exciton state. This corresponds to a 33-fold SHG signal amplification due to the

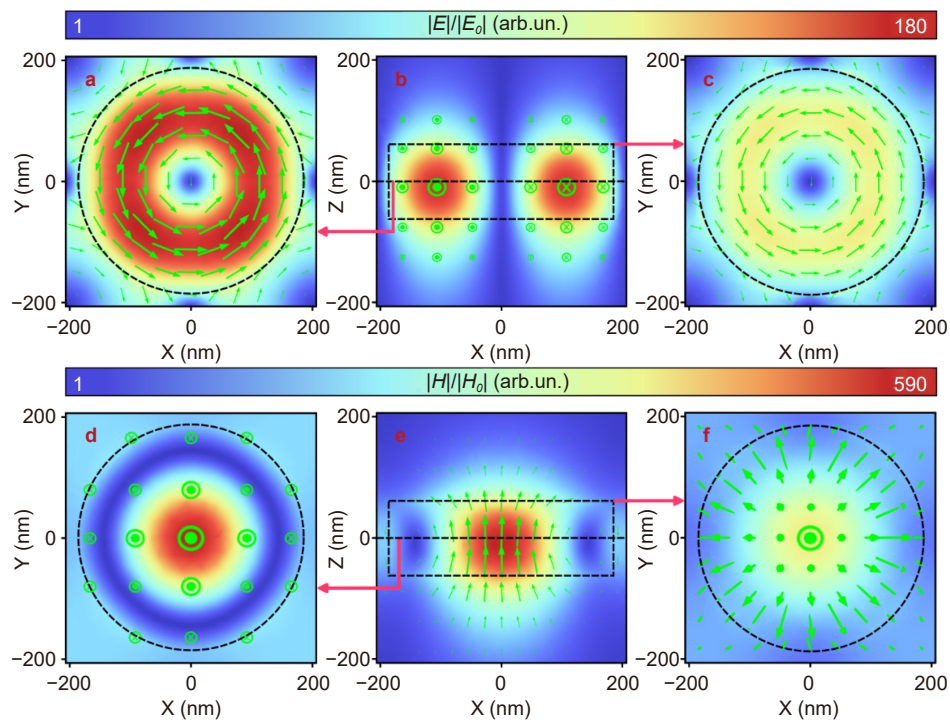


Fig. 3 | Normalized electric (a-c) and magnetic (d-f) field distributions inside a unit cell of the metasurface at $AOI = 1^\circ$ at the resonance wavelength of the quasi-BIC mode at 712 nm, respectively (cross sections at the middle of the disk's height: (a,d); cross sections through the disk diameter: (b,e); cross sections at the top of the disk: (c,f). Green arrows denote the electric and magnetic field directions.

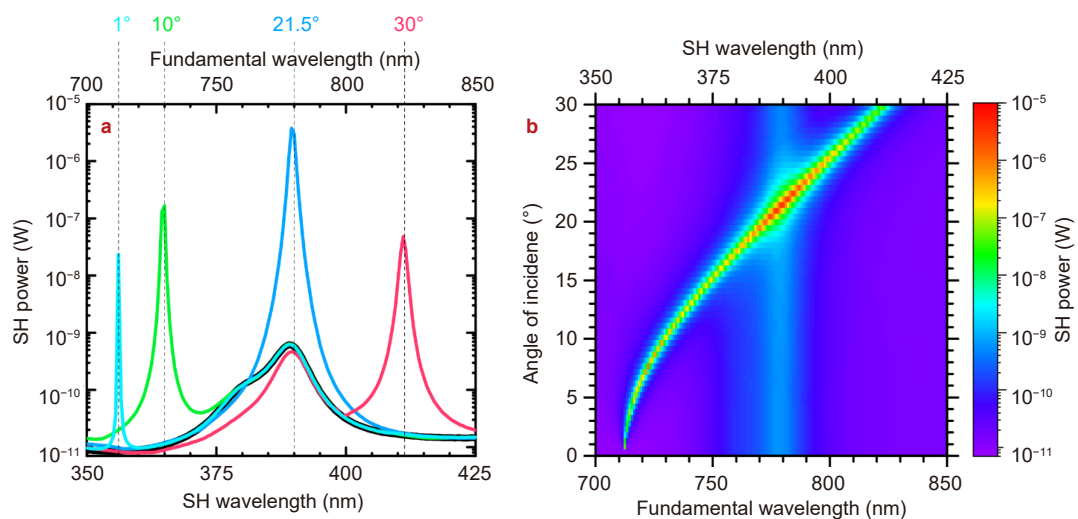


Fig. 4 | (a) Second-harmonic (SH) power spectra in a log-scale at various AOI : 0° (black curve), 1° (cyan curve), 10° (green curve), 21.5° (blue curve), 30° (red curve), (b) angular-resolved SH power spectrum in a log-scale.

presence of the metasurface resonance. The nonlinear signal at 10° turns out to be equal to 2×10^{-7} W at the fundamental wavelength of 730 nm and 6×10^{-10} W at the exciton position. The signal amplification due to the metasurface resonance is ~ 330 relative to the material resonance of the monolayer.

A similar situation is observed at $AOI = 30^\circ$. There are also two resonant features in the SH spectrum. The left one now is the exciton state with a signal magnitude of 5×10^{-10} W.

The right one is the quasi-BIC resonance with the magnitude of 5×10^{-8} W, which means a 100-fold increase in the signal due to the metasurface resonance.

The SH signal reaches the value of 4×10^{-6} W in the case of spectral overlap of the 2D material and metasurface resonances at 21.5° . This corresponds to an increase of the nonlinear signal of ~ 7000 times compared to the solitary exciton state and at least 20 times compared to the nonlinear signal from the quasi-BIC resonance at other AOI s. The

ratio of the maximum SH power at 21.5° (4×10^{-6} W) to that of the TMDC film on an unstructured layer of TiO₂ (1×10^{-10} W) is 4×10^4 (see Table 1). The efficiency of nonlinear conversion to the second harmonic can be estimated as 1.8×10^{-6} . For instance, the SHG conversion efficiency for single graphene nanoparticles is 10^{-8} ³². It has also been demonstrated that this efficiency reaches 10^{-6} in LiNbO₃ metasurfaces³³, while its typical value for metasurfaces based on III–V semiconductors is 10^{-5} , which is achieved in GaAs³⁴, AlGaAs³⁵ and GaP³⁶ nanodisk arrays. In the referenced works, the metasurfaces themselves serve as nonlinear materials with thicknesses of several hundred nanometers, in contrast to this paper, which features a nonlinear material with a thickness of only 0.75 nm. Table 1 summarizes the current achievements in SHG in hybrid systems of TMDCs coupled with nanostructured materials. It demonstrates that SH signal relative to nonstructured film in the current paper exceeds most of the results achieved in other works. The only research that surpasses our result exploits two BIC resonances and a nanostructured WS₂ monolayer¹².

We do not attempt to perform spectral overlap of the highest Q-factor quasi-BIC resonance and the exciton resonance of a dichalcogenide film. Instead, the design is dictated by the necessity of the metasurface resonance to correlate with the laser pump pulse bandwidth in order to achieve better efficiency of nonlinear effects⁴². That is, we designed the structural resonance to match the spectral width of conventional femtosecond laser pulses (~5 nm) typically used in nonlinear optical experiments.

Figure 4(b) shows a map of the SH power at various wavelengths and AOIs of fundamental radiation. It clearly illustrates the reasonability of the spectral overlap of both structural and material resonances. The SH signal from the bright exciton at 779 nm has a relatively low amplitude of approximately 10^{-10} W, which remains constant across various AOIs and is quite challenging to detect. In contrast, the structural resonance exhibits a larger amplitude of about

10^{-8} W and undergoes a redshift as the AOI increases. Continuous tuning of this BIC-induced second-harmonic resonance across the spectrally fixed exciton line reveals the significant enhancement at the spectral overlap with the signal reaching 10^{-6} W. In addition to the SHG enhancement, the map also indicates broadening of the quasi-BIC resonance as it approaches the exciton one, which is attributed to the exciton's significant spectral width of about 15 nm. In some experiments, such spectral broadening can enable an even better correspondence with the laser pump pulse bandwidth, thereby allowing for greater efficiency in SHG. For instance, a Ti: Sapp femtosecond laser can be used as a source of fundamental radiation illuminating the sample mounted on a piezo-stage for the precise AOI adjustment. The nonlinear signal can be detected by the photomultiplier tube with appropriate fundamental radiation filtration⁸.

Conclusions

In this work, the amplification of the second-harmonic signal by spectrally overlapping quasi-BIC resonance of the metasurface and material resonance of the TMDC film is shown. The SHG enhancement reaches 3 orders of magnitude compared to the solitary exciton. The hybrid metasurface under study is MoSe₂ monolayer placed on top of a 2D array of TiO₂ nanodisks. The efficiency of SHG in a dichalcogenide film depends on the relative spectral position of the metasurface resonance and the exciton resonance of the TMDC film. The highest SHG efficiency is reached in the case of the spectral overlap of these resonances, which is achieved by tuning the spectral position of the quasi-BIC resonance by means of varying the AOI of fundamental s-polarized radiation. The SH signal in this case is increased by 3 orders of magnitude compared to the solitary exciton resonance and by at least 20 times compared to the metasurface resonance at other angles of incidence.

Table 1 | Existing SHG enhancement of TMDCs coupled with nanostructured materials.

TMDC	Nanostructure	SHG enhancement relative to nonstructured film
1L-MoSe ₂	Si waveguide	5 times ³⁷
3R-MoS ₂ (110 nm thickness)	All-TMDC nanodisks	23-fold ⁹
1L-WSe ₂	Si photonic crystal cavity	200 ³⁸
1L-MoS ₂	Metasurface of Si cruciform-shaped silicon metaatoms	600 ³⁹
1L-WSe ₂	Multiple-hole Si-metasurface	2 orders ⁴⁰
1L-MoSe ₂	TiO ₂ metasurface	2 orders ¹⁰
3R-MoS ₂ (25 nm thickness)	All-TMDC metasurface of circular and triangular holes	3 orders ⁴¹
1L-WS ₂	Si metasurface of bar pairs	1140-fold ⁸
1L-WS ₂	Si hole metasurface	1580 times ¹³
1L-MoSe ₂	TiO ₂ disks metasurface	4 orders (this work)
1L-WS ₂	GaP photonic grating slab	7 orders ¹²

This method of increasing the efficiency of SHG can be of great importance in photonics. It provides the ability to adjust the spectral position of the resonance in the case of imprecise sample manufacturing and obtain large values of nonlinear signal, allowing for an increase in the efficiency of devices that operate on the basis of nonlinear-optical phenomena, such as lasers, ultrafast sensors, and optical communication systems.

References

- Wang QH, Kalantar-Zadeh K, Kis A et al. Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. *Nat Nanotechnol* 7, 699–712 (2012).
- Lee C, Yan HG, Brus LE et al. Anomalous lattice vibrations of single- and few-layer MoS₂. *ACS Nano* 4, 2695–2700 (2010).
- Cao LY. Two-dimensional transition-metal dichalcogenide materials: toward an age of atomic-scale photonics. *MRS Bull* 40, 592–599 (2015).
- Wang G, Chernikov A, Glazov MM et al. *Colloquium*: excitons in atomically thin transition metal dichalcogenides. *Rev Mod Phys* 90, 021001 (2018).
- Janisch C, Wang YX, Ma D et al. Extraordinary second harmonic generation in tungsten disulfide monolayers. *Sci Rep* 4, 5530 (2014).
- Malard LM, Alencar TV, Barboza APM et al. Observation of intense second harmonic generation from MoS₂ atomic crystals. *Phys Rev B* 87, 201401 (2013).
- Le CT, Clark DJ, Ullah F et al. Nonlinear optical characteristics of monolayer MoSe₂. *Ann Phys* 528, 551–559 (2016).
- Bernhardt N, Koshelev K, White SJU et al. Quasi-BIC resonant enhancement of second-harmonic generation in WS₂ monolayers. *Nano Lett* 20, 5309–5314 (2020).
- Popkova AA, Antropov IM, Tselikov GI et al. Nonlinear exciton-Mie coupling in transition metal dichalcogenide nanoresonators. *Laser Photonics Rev* 16, 2100604 (2022).
- Nazarenko AA, Chernyak AM, Musorin AI et al. Cryogenic nonlinear microscopy of high-Q metasurfaces coupled with transition metal dichalcogenide monolayers. *Nanophotonics* 13, 3429–3436 (2024).
- Nauman M, Yan JS, de Ceglia D et al. Tunable unidirectional nonlinear emission from transition-metal-dichalcogenide metasurfaces. *Nat Commun* 12, 5597 (2021).
- Hong PL, Xu L, Rahmani M. Dual bound states in the continuum enhanced second harmonic generation with transition metal dichalcogenides monolayer. *Opto-Electron Adv* 5, 200097 (2022).
- Shi JW, Wu XX, Wu KM et al. Giant enhancement and directional second harmonic emission from monolayer WS₂ on silicon substrate via Fabry-Pérot micro-cavity. *ACS Nano* 16, 13933–13941 (2022).
- Guo YH, Pu MB, Zhang F et al. Classical and generalized geometric phase in electromagnetic metasurfaces. *Photonics Insights* 1, R03 (2022).
- Luo XG. Multiscale optical field manipulation via planar digital optics. *ACS Photonics* 10, 2116–2127 (2023).
- Chernyak AM, Barsukova MG, Shorokhov AS et al. Bound states in the continuum in magnetophotonic metasurfaces. *JETP Lett* 111, 46–49 (2020).
- Lin DM, Fan PY, Hasman E et al. Dielectric gradient metasurface optical elements. *Science* 345, 298–302 (2014).
- Kruk S, Kivshar Y. Functional meta-optics and nanophotonics governed by Mie resonances. *ACS Photonics* 4, 2638–2649 (2017).
- Fang CZ, Yang QY, Yuan QC et al. High-Q resonances governed by the quasi-bound states in the continuum in all-dielectric metasurfaces. *Opto-Electron Adv* 4, 200030 (2021).
- Fan JX, Xue ZQ, Wang H et al. Hybrid bound states in the continuum in terahertz metasurfaces. In *2023 Cross Strait Radio Science and Wireless Technology Conference (CSRSWTC)* 1–3 (IEEE, 2023). <https://doi.org/10.1109/CSRSWTC60855.2023.10427381>.
- Shcherbakov MR, Neshev DN, Hopkins B et al. Enhanced third-harmonic generation in silicon nanoparticles driven by magnetic response. *Nano Lett* 14, 6488–6492 (2014).
- Zograf G, Koshelev K, Zalogina A et al. High-harmonic generation from resonant dielectric metasurfaces empowered by bound states in the continuum. *ACS Photonics* 9, 567–574 (2022).
- Zheng Z, Xu L, Huang LJ et al. Third-harmonic generation and imaging with resonant Si membrane metasurface. *Opto-Electron Adv* 6, 220174 (2023).
- Hsu C, Frisenda R, Schmidt R et al. Thickness-dependent refractive index of 1L, 2L, and 3L MoS₂, MoSe₂, WS₂, and WSe₂. *Adv Opt Mater* 7, 1900239 (2019).
- Koshelev K, Lepeshov S, Liu MK et al. Asymmetric metasurfaces with high-Q resonances governed by bound states in the continuum. *Phys Rev Lett* 121, 193903 (2018).
- Zhen B, Hsu CW, Lu L et al. Topological nature of optical bound states in the continuum. *Phys Rev Lett* 113, 257401 (2014).
- Evlyukhin AB, Fischer T, Reinhardt C et al. Optical theorem and multipole scattering of light by arbitrarily shaped nanoparticles. *Phys Rev B* 94, 205434 (2016).
- Evlyukhin AB, Chichkov BN. Multipole decompositions for directional light scattering. *Phys Rev B* 100, 125415 (2019).
- Xu L, Zangeneh Kamali K, Huang LJ et al. Dynamic nonlinear image tuning through magnetic dipole quasi-BIC ultrathin resonators. *Adv Sci* 6, 1802119 (2019).
- Wu MF, Ha ST, Shendre S et al. Room-temperature lasing in colloidal nanoplatelets via Mie-resonant bound states in the continuum. *Nano Lett* 20, 6005–6011 (2020).
- Wu MF, Ding L, Sabatini RP et al. Bound state in the continuum in nanoantenna-coupled slab waveguide enables low-threshold quantum-dot lasing. *Nano Lett* 21, 9754–9760 (2021).
- Smirnova DA, Shadrivov IV, Miroshnichenko AE et al. Second-harmonic generation by a graphene nanoparticle. *Phys Rev B* 90, 035412 (2014).
- Fedotova A, Younesi M, Sautter J et al. Second-harmonic generation in resonant nonlinear metasurfaces based on lithium niobate. *Nano Lett* 20, 8608–8614 (2020).
- Liu S, Sinclair MB, Saravi S et al. Resonantly enhanced second-harmonic generation using III-V semiconductor all-dielectric metasurfaces. *Nano Lett* 16, 5426–5432 (2016).
- Gili VF, Carletti L, Locatelli A et al. Monolithic AlGaAs second-harmonic nanoantennas. *Opt Express* 24, 15965–15971 (2016).
- Yang MY, Weissflog MA, Fedorova Z et al. Second harmonic generation in monolithic gallium phosphide metasurfaces. *Nanophotonics* 13, 3311–3319 (2024).
- Chen HT, Corbaliou V, Solntsev AS et al. Enhanced second-harmonic generation from two-dimensional MoSe₂ on a silicon waveguide. *Light Sci Appl* 6, e17060 (2017).
- Fryett TK, Seyler KL, Zheng J et al. Silicon photonic crystal cavity enhanced second-harmonic generation from monolayer WSe₂. *2D Mater* 4, 015031 (2016).

39. Wang JT, You JW, Panoiu NC. Giant second-harmonic generation in monolayer MoS₂ boosted by dual bound states in the continuum. *Nanophotonics* **13**, 3437–3448 (2024).
40. Ren PW, Huang Z, Luo S et al. Quasi-BICs enhanced second harmonic generation from WSe₂ monolayer. *Nanophotonics* **13**, 3449–3456 (2024).
41. Zograf G, Küçüköz B, Polyakov AY et al. Ultrathin 3R-MoS₂ metasurfaces with atomically precise edges for efficient nonlinear nanophotonics. *Commun Phys* **8**, 271 (2025).
42. Okhlopkov KI, Zilli A, Tognazzi A et al. Tailoring third-harmonic diffraction efficiency by hybrid modes in high-Q metasurfaces. *Nano Lett* **21**, 10438–10445 (2021).

Acknowledgements

We are grateful for the financial support from Russian Science Foundation (Grant No. 25-12-00355). The reported study in part of non-linear calculations is funded by Shenzhen Municipal Government and Shenzhen MSU-BIT University. A.A. Nazarenko acknowledges the Foundation for the Advancement of Theoretical Physics and Mathematics “BASIS” for the scholarship

award. B.S. Luk'yanchuk acknowledges MSU state assignment.

Author contributions

N.A.A. performed calculations, M.A.I. and L.B.S. proposed the original idea and F.A.A. supervised the project. All authors worked on the text.

Competing interests

The authors declare no competing financial interests.

Supplementary information

Supplementary information Supplementary information for this paper is available at <https://doi.org/10.29026/oep.2025.250003>



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/> ©The Author(s) 2025.

