Field canalization using anisotropic 2D plasmonics

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Optical devices capable of suppressing diffraction are of great technological importance to many nanophotonic applications. One important technique to achieve diffractionless optics is to exploit field canalization effect. However, current technological platforms based on metamaterial structures typically suffer from strict loss-confinement trade-off, or lack dynamic reconfigurability over device operations. Here we report an integrated canalization platform that can alleviate this performance trade-off. It is found that by leveraging material absorption of anisotropic 2D materials, the dispersion of this class of materials can flatten without increasing propagation losses and compromising confinement. The realization of such canalization can be considered using black phosphorus (BP), where topological transition from elliptic to hyperbolic curves can be induced by dynamically leveraging material absorption of BP. At the transition point, BP film can support long range, deeply subwavelength, near-diffractionless field propagation, exhibiting diffraction angle of 5.5°, propagation distance of 10λapp and λapp < λ/300.

INTRODUCTION

Technological platforms that can suppress the diffraction of light have been studied extensively as they can be utilized in applications that are restricted by diffraction limit such as near-field spectroscopy, microscopy, energy harvesting, construction of self-trapping devices and free-space optical communications1–8. For these applications, the diffraction angle along with propagation loss incurred to alleviate diffraction, are the two key attributes that dictate the performance of such nearly diffractionless optical devices. To date, implementations of low-loss, highly collimated beams typically rely on one of two mechanisms: nonlinear self-trapping9, and the propagation of non-diffracting Bessel beams10,11. For nonlinear self-trapping, the expansion of optical beams is delicately balanced by nonlinear-induced self-focusing, which collectively permit the beam to propagate without spatial diffraction. Nonetheless, the operation of such spatial soliton requires high input optical powers and is only limited to specific materials endowed with optical nonlinearity. On the other hand, non-diffracting Bessel beams can propagate with no need for nonlinear materials. However, the excitation of Bessel beams requires a delicate control over the phase and amplitude of the wavefronts forming the beams9. This inevitably increases the complexity of the system and its operation, particularly in guided-wave settings that are compatible with integrated photonics. Extra structures such as subwavelength nanostructured elements12 or photonic crystal structures13,14 need to be deployed to assist in the generation of such beams. These resonant structures inherently impact device operational bandwidth and do not offer the ability to dynamically tune the optical properties, making them mostly intended for a limited suite of applications.

An alternative approach that enables the suppression of optical diffraction is to exploit metamaterials and plasmonics15,16. Through leveraging the material’s anisotropy, the dispersion of metamaterials can flatten in the epsilon-near-zero (ENZ) regime, which permits all wave harmonics to propagate in the same direction, allowing the fields to canalize without diffraction. On the other hand, plasmonics can also support optical fields on the subwavelength scale, facilitating the constructions of diffractionless devices in conjunction with achieving such effect with nano-scale confinement17,18. This can enhance wave-matter interaction and hence passive and active integrated devices figure of merit. However, the performance of ENZ-based devices is typically compromised by the excessive material absorption that is inherent to the material constituents of such devices, which drastically curtails the propagation length of the canalized beams16. In contrast, metamaterials with ultrahigh material absorption are capable of supporting low-loss canalized field17,18. In this case, the optical field overlapping lossy materials can be minimized, reminiscent of perfect electric conductor (PEC) effect where the electric field resident in PEC can diminish due to infinite material absorption. Nevertheless, this technique will severely impact optical field confinement, and the high material absorption is also not directly achievable in most of the natural anisotropic materials, hence further implementation of artificial metastructures is required18–20. Recently, by stacking two hyperbolic metasurfaces, a highly confined, low-loss optical canalization scheme based on Moire physics has been demonstrated21,22. However, the dispersion band depends sensitively on the rotation angle between the two materials, and the operation of canalization regime can only be attained within a narrow range of twisted angle.

In this work, we demonstrate theoretically that with the use of only one layer film anisotropic 2D material23–25, one can achieve a previously unexplored design strategy capable of supporting low-loss canalization of highly confined plasmon waves. By leveraging material absorption which is naturally intrinsic in these materials, it is found that in addition to elliptic and hyperbolic dispersion regimes which are common in ordinary metamaterials, this class of 2D material can possess a combination or a hybrid of elliptic and hyperbolic characteristics. This allows dispersion contours to flatten when transitioning from closed to open dispersion regimes. Notably, such a transition mechanism is not induced by the change in sign of permittivity in ENZ material or by the control of rotation angle that dictates the hybridization of two metasurfaces, but through the strength of the material absorption. As such, material absorption, which generally represents an
unwanted shortcoming for plasmonic structures, can instead be positively exploited to tailor dispersion characteristics of anisotropic 2D material structures and enable new optical functionality. Moreover, the material absorption introduced here will not negatively impact the modal loss and confinement of the plasmonic waves, and the level of material absorption required for canalization is readily available in natural 2D materials such as black phosphorus (BP) when compared to using PEC effect as shall be demonstrated. The possibilities of dispersion engineering of plasmon modes in 2D anisotropic materials thus render them a promising integrated plasmonic platform for diffractionless optics, while allowing strong tunability over device operations using gate voltage.

RESULTS AND DISCUSSIONS

Dispersion engineering in anisotropic 2D materials

Plasmonic waveguides, constructed using 2D plasmonic materials have emerged as a popular optical platform for the realization of photonic devices on a deep subwavelength scale. Plasmonic waveguides using 2D layers can offer the highest level of modal confinement, unprecedented device tunability and enhanced local density of states14,26. In particular, 2D plasmonic materials with anisotropic optical properties have received significant attention due to their potential to connect and concomitantly proportionately to metamaterial-based functions and metacircuit realized in a 2D flat surface. In this work, we will discuss the opportunities afforded by leveraging material absorption to achieve flatband dispersion within anisotropic 2D materials, which can allow canalization of optical fields in a 2D integrated setting. The dispersion relation of an anisotropic 2D film with in-plane anisotropic conductivity tensor \( \sigma_{x,z} \), can be characterized by the following equation28:

\[
(k_z^2 - k_0^2)\sigma_x + (k_z^2 - k_0^2)\sigma_z - 2i\sqrt{k_z^2 + k_0^2 - k_z^2 \left( \frac{1}{\eta_0} + \frac{\eta_0\sigma_x\sigma_z}{4} \right)} = 0
\]

(1)

It is instructive to first consider the effect of material absorption on the dispersion properties in isotropic 2D materials such as graphene, where the optical properties are characterized by material’s in-plane conductivity (\( \sigma \)) as schematically shown in Fig. 1a. In the non-retarded regime, the isotropic 2D dispersion can be obtained by assuming \( \sigma_x = \sigma_z = \sigma \) in Eq. (1), which yields29:

\[
\sqrt{k_z^2/k_0^2 + k_z^2/k_0^2} = \frac{2}{\eta_0} \frac{\sigma_i + i\sigma_r}{|\sigma|^2}
\]

(2)

The plots in Fig. 1b, c display the effect of material absorption on isotropic dispersion based on Eq. (2). Without loss of generality, here we assume that the field is propagating in the z direction, and the dispersion behaviors of \( k_z \) are plotted as function of \( \text{Re}[k_z] \), which represents waves of different harmonics. It can be seen that the introduction of material absorption (\( \text{Re}[\sigma] \)) will lead to the reduction and enhancement in \( \text{Re}[k_z] \) and \( \text{Im}[k_z] \), respectively, which negatively impacts modal confinement and propagation distance of 2D isotropic plasmons.

In contrast, the mechanism for anisotropic dispersion of 2D materials with material absorption becomes more complex, especially in the regime where \( \text{Re}[\sigma_x] > \text{Im}[\sigma_x] \). Initially, we study the dispersion behavior when \( \sigma_x \) is a real quantity (\( \text{Im}[\sigma_x] = 0 \)). As detailed in the supplementary material, the dispersion relation in this case can be expressed as:

\[
\sigma_xk_z^2 - \sigma_z^2k_0^2 - \frac{2}{\eta_0} \sqrt{\sigma_z^2k_0^2} = 0
\]

(3)

It can be observed that when \( \text{Im}[\sigma_x] = 0 \), the dispersion of anisotropic 2D materials can be characterized by a biquadratic equation, which exhibits parabolic features similar to those of hyperbolic dispersion as displayed in Fig. 1h. It is noteworthy to point out that similar dispersion behavior can also be observed in 3D metamaterials operated in the ENZ regime (\( \text{Im}[\varepsilon] > \text{Re}[\varepsilon] \sim 0 \)). In this case, the dispersion can become parabolic even though the real part of permittivity tensor is positive.

The evolution of dispersion of the \( \text{Re}[k_z] \) with respect to material absorption (\( \text{Re}[\sigma_x] \)) is further displayed in Fig. 1e–h. It is shown that anisotropic 2D materials can exhibit elliptic, parabolic, and a mixed type of dispersion depending on the value of \( \text{Re}[\sigma_x] \). In Fig. 1f, h, the dispersion contours are closed and open curves in the regimes where \( \text{Re}[\sigma_x] < \text{Im}[\sigma_x] \) and \( \text{Re}[\sigma_x] > \text{Im}[\sigma_x] \), respectively. On the other hand, the mixed dispersion can occur with moderate material absorption (\( \text{Re}[\sigma_x] \approx \text{Im}[\sigma_x] \)), which exhibits a combination of elliptic and parabolic dispersion as displayed in Fig. 1g.

As evidenced from the results, material absorption offers a path toward dispersion engineering, making it possible to transition from close to open dispersion through the leverage of the strength of material absorption. Such a transition can be verified in Fig. 1i–k, which illustrate the field distributions in 2D anisotropic material launched by a dipole polarized in the out of plane direction. It is shown that a more diffracting, elliptic wavefront is observed in the low material absorption regime, whereas a more confined, hyperbolic-like wavefront can be observed in the high material absorption regime. In the intermediate regime, the anisotropic 2D materials instead can support an elliptic, but a more confined wavefront as depicted in Fig. 1j; a feature corresponding to mixed type of dispersion. It should be highlighted that such a feature cannot be obtained in isotropic materials, where the wavefront is always circular in nature regardless of the strength of material absorption as shown in Fig. 1d.

It is noteworthy to highlight two important attributes of the mixed type dispersion supported in such anisotropic 2D materials. Because the contour depicts elliptic-like dispersion for smaller \( k_z \) and parabolic-like dispersion for larger \( k_z \), there exists a transition point at which the slope (\( \text{d}k_z/\text{d}k_0 \)) of the curve becomes zero. As detailed in the supplementary materials, the value of \( k_z \) corresponding to this point can be obtained by assuming \( \text{d}k_z/\text{d}k_0 = 0 \) in Eq.(1), which is given by:

\[
\frac{k_z}{k_0} = \frac{1}{\eta_0|\sigma_x|} \sqrt{\frac{\text{Im}[\sigma_x]}{\text{Im}[\sigma_z]}}
\]

(4)

On the other hand, in the high \( k_z \), non-retarded regime, the slope of dispersion curve in the parabolic/hyperbolic-like regime is also derived in the supplementary material, and can be expressed as:

\[
\frac{\text{d}\text{Re}[k_z]}{\text{d}k_z} = \frac{\text{Re}[\sigma_x]}{2\text{Im}[\sigma_z]}
\]

(5)

From Eqs. 4 and 5, it is seen that in this case the slope of the curve in the high \( k_z \) regime is predominantly characterized by material absorption, which in turn can confirm the dispersion curve obtained in the high \( \text{Re}[\sigma_x] \) regime in Fig. 1h.

In the field of metamaterials, similar mixed/hybrid dispersion can also occur in bianisotropic materials29, which are described by high order dispersion relations with circularly or elliptically polarized eigenwaves, or parity time (PT) symmetry
metamaterials which involve spatial modulation of loss and gain. However, these approaches involve the interaction of light with subwavelength nanoparticles and are mostly intended for free-space applications due to the flow of light from and into surfaces orthogonally, rather than in-plane. In contrast, naturally occurring 2D materials are better suited as an integrated in-plane platform due to their structural simplicity. The mixed type of dispersion afforded in anisotropic 2D materials therefore can facilitate new integrated optical functionalities that are not possible in conventional elliptic and hyperbolic metamaterials. Markedly, it indicates the possibility of topological transition from elliptic to hyperbolic dispersion as a functional regime where devices can be built and

Fig. 1 Dispersion of anisotropic 2D materials. a Schematic of an isotropic 2D material sitting on the x-z plane, which is optically characterized by in-plane conductivity $\sigma$. Dispersion contours of (b) $\text{Re}[k_z]$ and (c) $\text{Im}[k_z]$ of an isotropic 2D material as function of $k_x$ using various values of $\text{Re}[\sigma]$. It is seen that the increase in material absorption ($\text{Re}[\sigma]$) will lead to the reduction in $\text{Re}[k_z]$ and the increase in $\text{Im}[k_z]$, which is considered as a shortcoming for 2D plasmon due to reduced propagation distance. d For isotropic 2D films, the wavefront launched by a $y$-polarized electric dipole is always circular regardless of the strength of material absorption. e Schematic of an anisotropic 2D material characterized by an in-plane anisotropic conductivity tensor ($\sigma_{x,z}$). Contrary to isotropic 2D films, anisotropic 2D materials can support (f) elliptic, (h) hyperbolic, and (g) mixed type of dispersion depending on the strength of material absorption ($\text{Re}[\sigma_{x,z}]$/$\text{Im}[\sigma_{x,z}]$). For mixed dispersion, the dispersion contour can possess a hybrid character of the elliptic and hyperbolic dispersions. When launched by a $y$-polarized dipole, anisotropic 2D films therefore can support (i) elliptic, or (k) hyperbolic field distributions in the low and high material absorption regimes. (j). In the intermediate regime, mixed type of field distribution can be supported, which offers a pathway toward dispersion transition.
Such a transition is of great interest to plasmonic metadevices because the dispersion contour can be tailored by regulating material absorption. In the next section, we will demonstrate how to further leverage such dispersion characteristics to achieve plasmon canalization in 2D materials for diffractionless optics.

**Field canalization in anisotropic 2D materials facilitated by material absorption**

The mixed type dispersion in anisotropic 2D materials can provide new opportunities to achieve optical functions unattainable in their isotropic counterparts. In particular, the existence of a transition point along with the control over the slope of the curve in the open regime, allows the dispersion to flatten by leveraging material absorption. Because the slope in the elliptic and hyperbolic regimes are predominantly dictated by degree of anisotropy ($\text{Im}(|\sigma_z|)/\text{Im}(|\sigma_x|)$) and the material absorption respectively (Eq. 5), one can define the following condition to achieve flatband dispersion in anisotropic 2D materials:

$$\text{Im}(|\sigma_x|) > \text{Im}(|\sigma_z|) \approx \text{Re}(|\sigma_z|).$$  \hfill (6)

Figure 2a, b illustrate an example as to how to leverage material absorption to achieve flatband dispersion based on Eq.(6). It is seen that for an anisotropic 2D film free of material absorption ($\text{Re}(|\sigma_z|)=0$), the dispersion curve will exhibit an elliptic characteristics when $\text{Im}(|\sigma_z|)=0.1,0.2\text{mS}$ as depicted by the blue curve in Fig. 2a. However, by increasing the strength of material absorption such that $\text{Re}(|\sigma_z|) \approx \text{Im}(|\sigma_z|)$, the initial, closed, elliptic dispersion contour can become open and the mixed type of dispersion will be supported. The opening angle of the curve can be tuned by using various values of $\text{Re}(|\sigma_z|)/\text{Im}(|\sigma_z|)$ as depicted by the red ($\sigma_z=0.01i+0.06\text{mS}$) and black ($\sigma_z=0.4i+0.3\text{mS}$) curves. On the other hand, the dispersion curve will become predominantly hyperbolic when $\text{Re}(|\sigma_z|)$ further increases, losing the elliptic feature as plotted by the green curve in Fig. 2a.

Such a material absorption-induced transition can be further examined in Fig. 2b, which details the dispersion characteristics in the regime wherein $-100 < k_x/k_0 < 100$. Due to the emergence of a transition point pertaining to the mixed type of dispersion, a more flattened contour curve can be obtained in this regime when $\text{Im}(|\sigma_z|) < \text{Im}(|\sigma_x|)$ with the use of moderate material absorption as given by Eq.(5). This dispersion feature, in turn, can facilitate field canalization in anisotropic 2D materials, which requires the Poynting vector of different $k_x$ modes to have the same direction. As depicted in Fig. 2c, the Poynting vector can become unidirectional ($\theta=0$) for a broad range of $k_x$ modes when $\text{Re}(|\sigma_z|) = \text{Im}(|\sigma_z|)$, hence allowing modes of different spatial harmonics to canalize in the same propagation direction.

When launched by a dipole source, the canalization effect enabled by flattened dispersion can suppress the diffraction of the propagating field, permitting a broad range of $k_x$ harmonics to propagate in the same direction. To assess the effect of canalization induced by material absorption, we compare the canalization angle, defined by $\Delta$FWHM/$\Delta$d$^{22}$, as function of $\text{Re}(|\sigma_z|)$ as plotted in Fig. 2d, where FWHM is the full width half maximum of the wavefront and $\Delta$d is the propagation distance of the fields. The expansion of the wavefront can be optimally suppressed...
when \( \text{Re}[\sigma_z] \approx 0.6\text{Im}[\sigma_z] \). In this case, the canalization angle can be as small as 13°, indicative of the possibility of field canalization through the regulation of material absorption.

It is important to note that diffraction can be further suppressed through the interplay between material absorption and anisotropy for the best performance of canalization. As displayed in Fig. 2f, it is seen that with the same level of material absorption (\( \text{Re}[\sigma_z] = 0.6\text{Im}[\sigma_z] \)) being used, the canalization angle can be reduced further by increasing the degree of material anisotropy (\( \text{Im}[\sigma_y]/\text{Im}[\sigma_z] \)). This is due to a broader range of canalized \( k_z \) modes achievable in anisotropic 2D materials when using a stronger degree of material’s anisotropy on top of material absorption, as illustrated in Fig. 2e. Also shown in the plot is the open angle, which can offer an analytical estimation of the canalization effect based on the slope in the hyperbolic regime (\( \tan^{-1}(\text{Re}[\sigma_z]/2\text{Im}[\sigma_z]) \)). It is evident that the trend in the canalization angle shows good agreement with that of open angle, which suggests that the stronger canalization effect is because dispersion can be flattened into the higher \( k_z \) regime as shown by the green curve in Fig. 2e.

### Loss and confinement trade-off in 2D canalized structures

In this section, we will show how the material absorption-induced flatband dispersion can be engineered to enable low loss, highly confined canalized fields when compared to other canalized techniques based on ENZ and PEC effects. This can address the design bottleneck that is common in plasmonic devices, where material absorption typically dictates strict trade-offs between modal loss and confinement. For instance, for canalization through using ENZ effects, the material absorption will greatly reduce the propagation length of the canalized plasmon fields whereas in the PEC scheme, low-loss canalized plasmon fields can be obtained but subwavelength confinement of the modes will be compromised. It should be noted that similar design trade-off has been recently addressed using composite hybrid plasmonic structures, which can facilitate device performance of various plasmonic functional devices. Anisotropic 2D materials can instead offer a platform to achieve superior canalized mode attributes without the need for implementing layered waveguide structures, while simultaneously offering strong device tunability.

Counter-intuitively, the low-loss canalized field achieved in this work is facilitated by regulating material absorption such that \( \text{Re}[\sigma_z] \approx \text{Im}[\sigma_z] \). This is in stark contrast to conventional design wisdom, which dictates that the formation of low-loss plasmonic modes should require the functional plasmonic materials to be operated either in low or ultrahigh material absorption regimes, such as the ones in ENZ and PEC canalized schemes respectively. To understand how moderate material absorption can impart such a low-loss canalization effect, in the supplementary material we study the dispersion behavior of the real and imaginary components of \( k_z \) as a function of \( k_x \). As can be seen, the material absorption introduced here has a disproportional effect on the modal loss in the elliptic and parabolic regimes, as \( \text{Im}[k_z] \) increases more significantly only after the transition point into the hyperbolic regime. As such, a broad range of low-loss \( k_z \) modes can still be achieved in the elliptic regime, which in turn permits low-loss canalized field propagation.

An important figure of merit for plasmonic modes is the ratio of \( \text{Im}[k_z] \) over \( \text{Re}[k_z] \), which reflects the length of propagation distance of the plasmon modes normalized to the wavelength of operation. Additionally, confinement of the modes can be estimated by the penetration depth (\( l_p \)) into the vacuum, as defined by \( \text{Im}[k_z] / 2\lambda_0 \). Such a metric has been utilized widely to characterize the confinement of plasmonic modes. Based on these two metrics, we can compare the modal loss and confinement of different 2D canalized schemes as functions of material absorption and \( k_z \), which are plotted in Fig. 3.

As displayed in Fig. 3a–c, the increased material absorption in the scheme we describe in this work can enable a relatively broadband, low-loss dispersion in the elliptic operating regime. Furthermore, the modal confinement is nearly unaffected, indicating that all spatial harmonics can still carry deeply subwavelength information, despite the presence of material absorption.

Conversely, the material absorption in ENZ canalized scheme represents an undesired shortcoming to the quality of plasmonic modes. As can be seen in Fig. 3d–f, the increased material absorption will negatively impact the modal loss and confinement, therefore degrading the performance of canalized plasmon fields. As such, material absorption should be minimized for the best performance of ENZ canalization. On the other hand, in the PEC scenario shown in Fig. 3g–i, the 2D materials should be operated in the ultrahigh regime to support low-loss plasmonic canalized fields. However, as displayed in Fig. 3j, the modal confinement will be severely compromised in the low \( k_z \) regime, inevitably losing subwavelength features originally offered by 2D plasmonics. Similar design trade-off associated with ENZ and PEC canalized schemes can also be observed in their 3D metamaterial version as discussed in the supplementary material. Overall, as showcased in Fig. 3a, d and g, the afforded mixed type of plasmonic modes can offer strong tunability over wavefront manipulation in BP chemical potential or electrical bias, which can offer strong tunability over wavefront manipulation in BP film as schematically depicted in Fig. 4a. For instance, Fig. 4b displays the conductivity tensor of 20 nm BP as a function of chemical potential in the MIR regime when \( \lambda_0 = 3.25\mu\text{m} \), where \( x \) and \( z \) are the armchair and zigzag directions of BP, respectively. The strength of material absorption in \( \sigma_z \) can be tuned significantly as a function of applied chemical potential. The canalization condition based on Eq.(6) can be therefore achieved in the vicinity of \( \mu = 0.08 \text{eV} \), where \( \text{Re}[\sigma_z] \approx \text{Im}[\sigma_z] \).

A dynamical topological transition from elliptic (\( \mu = 0.1 \text{eV} \)) to hyperbolic (\( \mu = 0.06 \text{eV} \)) contours can be realized, while the transition point corresponds to flattened dispersion (\( \mu = 0.08 \text{eV} \)) as shown in Fig. 4c. BP film operated with this condition can enable highly collimated canalized fields as illustrated in the field distributions within Fig. 4e. In this case, BP can support long range, highly canalized field with a diffraction angle of 5.5° and propagation distance of 5\( \lambda_{\text{opt}} \), highlighting BP’s potential as a tunable diffractionless material platform. It should be noted that the transition mechanism here is induced by regulating the material absorption, provided that the dispersion of the functional anisotropic materials can sweep across the point where the strength of material absorption is moderate (\( \text{Re}[\sigma_z] \approx \text{Im}[\sigma_z] \)). On the other hand, the diffraction angle of BP operated under the
ENZ condition ($\mu = 0.075 \text{eV}$) will increase to 15° with a reduced propagation distance of $2\lambda_{\text{app}}$. In this case, the dispersion curve will become hyperbolic-like which will lead to a more diffracting field propagation. Since the strength of material absorption can be tuned through chemical potential or bias in 2D materials, such a transition can be viable in most of the anisotropic 2D materials but not limited to BP.

Table 1 further compares the optical performance of various canalization platforms, where metamaterials can be realized using metal-dielectric structures\textsuperscript{19,20}. There are at least two major dispersion characteristics that are distinct from those of BP counterpart. First, the range of $k_x$ modes in the canalization regime in metamaterials ($-5 < k_x/k_0 < 5$) is about two order magnitude smaller than that of BP ($-300 < k_x/k_0 < 300$), which hinders higher $k_x$ harmonics from contributing canalization process. As such, BP plasmonics allow for better near-diffractionless propagation as compared with metamaterials, with a diffraction angle of only 5°. Second, the value of $\text{Re}[k_x]$ in the canalized regime in metamaterials based on metal is also around two order magnitude smaller than that of BP. The capability of 2D materials such as BP to support highly confined surface mode with guided wavelength ($\lambda_{\text{app}}$) much smaller than $\lambda_0$ make them a more favorable platform of choice for one to realize canalized fields in strongly subwavelength regime. In contrast, the guided wavelength supported in metamaterial or metal plasmonics will be within the same order as $\lambda_0$. In order to, account such subwavelength feature enabled by 2D materials, the figure of merit for the modal loss of 2D plasmonic is defined by $\text{Im}[k_x]/\text{Re}[k_x]$, which indicates the propagation distance normalized to guided wavelength\textsuperscript{15}. Clearly, through the regulation of material absorption, anisotropic 2D plasmonic material can represent a new paradigm for the constructions of diffractionless devices, while simultaneously facilitating long range, highly canalized field in the deep subwavelength regime.

![Fig. 3](https://example.com/f1.png)  
Fig. 3  Loss-confinement for different canalized schemes. Comparison of modal loss ($\text{Im}[k_x]/\text{Re}[k_x]$) and confinement ($L/\lambda_0$) in different 2D canalized platforms based on: (a)–(c) material absorption shown in this work, (d)–(f) ENZ effect, and (g)–(i) PEC effect. Larger penetration depth ($L$) will lead to weaker modal confinement.  

In-plane, integrated canalization platform in 2D material structures

In this section, we will discuss the attributes of anisotropic 2D materials as an attractive integrated photonic platform where field canalization can be configured in an in-plane, guided-wave setting without the need for combining other cladding layers to create 3D stacks. Integrated photonic devices can offer greater stability, density and scalability than their free space counterpart. Most importantly, by exploiting the anisotropic optical properties, these anisotropic materials can play the role of optical nanocircuit elements analogous to microelectronics27. Thus, an integrated platform that can support low loss, subwavelength field canalization with dynamic reconfigurability is highly desired. However, these important attributes may not be obtainable simultaneously with the use of current technological platforms.

For instance, with the use of twisted bilayer hyperbolic metasurfaces such as α-MoO3, a tunable, low loss, deeply subwavelength, and canalized plasmon scheme can be achieved21. Such a platform is based on the dispersion hybridization between anisotropic plasmon polaron fields in stacked α-MoO3, reminiscent of the peculiar electronic band structure modified by van-der-Waals superlattices36. More recently, it is demonstrated that such a bilayer twisted structure can be deployed to effectively create longitudinal spin of plasmon necessary for chiral plasmonics37,38. However, despite the numerous emerging photonic applications that twisted optics
can enable, the requirement of stacking two films in the out-of-plane direction makes it more suitable for free space optical elements. Additionally, the dispersion of such bilayer structures depends sensitively on the twisted angle between the films, which is not tunable therefore limits its capabilities for active applications. On the other hand, a coplanar scheme based on the PEC\(^4\) effect has also been proposed to achieve plasmon canalization. However, the operation of this scheme should require the implementation of composite subwavelength metastructures to achieve the desired material parameters. The actual canalization performance, based on such periodic structures, will be restricted by optical nonlocality\(^2\), particularly in the in-plane, integrated setting where such nonlocal optical effect will be more pronounced with the presence of in-plane wave vector. Additionally, similar to bilayer hyperbolic canalized scheme, the implementations of densely packed multilayer structures in these platforms will lead to higher optical loss more stringent to material granularity and impurity, which degrades the quality of canalized plasmon fields. In contrast, the canalization scheme facilitated by material absorption proposed in this work will not have these challenges as flatband engineering can be accomplished with the use of only single anisotropic 2D film which can be gate tunable in an in-plane, integrated setting.

To highlight the possibility of anisotropic 2D material as an integrated canalization platform, an in-plane excitation scheme involving an unbounded BP film connected to a BP ribbon waveguide of finite width can be considered, as schematically depicted in Fig. 4g. BP can suppress optical diffraction even when the ribbon mode \((\lambda < 0)\) enters the unbound regime \((\lambda > 0)\), maintaining highly confined Gaussian field profiles as the mode propagates down further into the film when \(\mu = 0.08\) eV. It should be noted that although similar diffractionless field propagation has also been reported using graphene solitons enhanced by graphene plasmonic\(^2\), no nonlinear effect is required in this work as the canalization is due to flatband dispersion enabled by material absorption.

Compared to other integrated diffractionless techniques, the flatband engineering in 2D anisotropic materials can allow field canalization in 2D integrated plasmonic without the need for combining other 3D structures. For instance, propagation of diffraction-free Bessel beam in an integrated, guided-wave setting has been recently reported\(^9\). However, the generation of such Bessel-type beam based on axion lens approach requires delicate controls over the phase and amplitude of the propagating waves. As such, phase controlling elements such as optical nanoresonators or photonic crystals should be deployed\(^10,40\) for the operation of axion lens. The inclusions of these resonator structures will lead to higher losses, bulkier device footprint, and restricted bandwidth of operation with limited device reconfigurability. Contrarily, our platform based on flatband engineering can represent a more advantageous platform as no such supporting structures are needed in the design. As a whole, anisotropic 2D materials can offer a planar 2D integrated canalization scheme that is readily available in naturally occurring materials, while simultaneously facilitate low loss and subwavelength plasmon propagation with no need to relying on additional 3D structures.

In summary, we have elucidated a physical mechanism where material absorption can be exploited to facilitate dispersion engineering in anisotropic 2D materials. It is found that by regulating material absorption, the dispersion contour can flatten, allowing low-loss plasmon canalization in the subwavelength regime with strong tunability. Some of these capabilities can be achieved in other 2D or 3D metastructures, but not with the dynamic reconfigurability nor performance that a single layer of anisotropic 2D material provides. The realization of such canalization effect can be immediately considered using natural anisotropic 2D materials such as BP. Because the conductivity and the strength of material absorption of BP can be dynamically configured through bias or chemical potential, topological transition process therefore can be observed via bias using BP film. When the dispersion flattens, BP can support low-loss canalization field with a diffraction angle of 5.5°. In addition to near-diffractionless propagation, we also envision that the versatility of dispersion supported in this class of 2D materials, namely capable of supporting elliptic, hyperbolic-like, and mixed type of contour behaviors through bias or doping, can represent a promising material platform to achieve new functionalities for 2D plasmonic metamaterials.

**METHODS**

**Optical modeling and simulations of 2D plasmonics**

The dispersion plots are obtained by solving Eq. (1) using Mathematica. The simulations of the dipole radiation profile are conducted using *Lumerical FDTD*, where the electric dipole is placed at the center of the film. The mesh size was set to be \(\lambda_0/5000\) around the film due to the deeply subwavelength feature of 2D materials.

**DATA AVAILABILITY**

The data that support the plots and findings within this paper are available from the corresponding author upon reasonable request.

Received: 29 September 2021; Accepted: 1 December 2021; Published online: 13 January 2022

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ACKNOWLEDGEMENTS

This project was funded by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

AUTHOR CONTRIBUTIONS

P.C. and A.S.H. conceive the idea and perform the analysis showcase in this work. C.L. contributes to BP models that are used in this work. P.C., C.L., and A.S.H. analyzed and wrote the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41699-021-00283-4.

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