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Normal Doppler Frequency Shift in Negative Refractive-Index Systems

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Besides the well-known negative refraction, a negative refractive-index material can exhibit another two hallmark features, which are the inverse Doppler effect and backward Cherenkov radiation. The former is known as the motion-induced frequency shift that is contrary to the normal Doppler effect, and the latter refers to the Cherenkov radiation whose cone direction is opposite to the source's motion. Here we combine these two features and discuss the Doppler effect inside the backward Cherenkov cone. We reveal that the Doppler effect is not always inversed but can be normal in negative refractive-index systems. A previously un-reported phenomenon of normal Doppler frequency shift is proposed in a regime inside the backward Cherenkov cone, when the source's velocity is two times faster than the phase velocity of light. A realistic metal-insulator-metal structure, which supports metal plasmons with an effective negative refractive index, is adopted to demonstrate the potential realization of this phenomenon.

1. Introduction

In his seminal work of negative refractive-index materials in 1968 [1], the Russian physicist Victor G. Veselago (1929-2018) proposed three exotic phenomena, namely, the negative refraction, the inverse Doppler effect, and the backward Cherenkov radiation (characterized by a backward Cherenkov cone opposite to the source's motion). While the absolute existence of negative refraction has caused substantial debates in past decades [2-5], the phenomena of inverse Doppler effect [6-16] and backward Cherenkov radiation [17-20] in negative refractive-index materials have never been questioned. As a result, it has been widely considered that the Doppler effect in a negative refractive-index material is always inversed, i.e., the Doppler frequency shift in such a material is negative (positive) when the source approaches (leaves) the observer. Moreover, the connection between the inverse Doppler effect and the backward Cherenkov cone has never been discussed, although both phenomena are caused by source's motion in negative refractive-index materials. Here we show that the Doppler effect in negative refractive-index materials is not always reversed but can be normal in a regime inside the backward Cherenkov cone, when the source's velocity v is two times faster than the phase velocity v_p of light, i.e., $v > 2|v_p|$. Because of the superlight velocity of source [21-26], we denote this phenomenon as the superlight normal Doppler effect in negative refractive-index systems. Such a finding is inspired by our recent work of the superlight inverse Doppler effect in *positive*-refractive index systems [26], which also appears if $v > 2|v_p|$.

It is V. L. Ginzburg and I. M. Frank, who noticed in 1947 that in positive refractive-index materials the Doppler effect near the Cherenkov cone exhibits anomalous properties [21-26]. They showed that when crossing the Cherenkov cone, the frequency of emitted photons will transit from positive to negative [22,23]. The criterion for this phenomenon is that the source's velocity needs to be faster than the phase velocity of light, which is the same as the Cherenkov threshold [22,23]. In other words, such an anomalous Doppler frequency shift is intrinsically connected with the Cherenkov cone. However, their discussion was limited to positive refractive-index systems.

Here we extend Ginzburg and Frank's theory of superlight Doppler effect [22,23] into negative refractive-index systems, and we discuss the possibility of constructing a normal Doppler frequency shift in such systems. As a concrete example, the highly squeezed polaritons with their effective refractive index being negative, such as the negative refractive-index metal plasmons in a metal-insulator-metal structure (where the group velocity and phase velocity are antiparallel) [27,28], are adopted as a potential platform to demonstrate this normal Doppler frequency shift in negative refractive-index systems. The procedure of the analytical derivation here follows our recent work [26], where the superlight normal and inverse Doppler effects were firstly discussed but limited to positive refractive-index systems.

2. Results and Discussion

To get a straightforward understanding of the normal Doppler frequency shift in negative refractive-index systems, we schematically illustrate the Doppler effect in time domain in Figure 1. Without loss of generality, we consider a radiation source that moves with a velocity $\vec{v} = +\hat{z}v$ and has a natural positive angular frequency ω_0 in the moving source frame. In the laboratory frame, the received radiation fields have a frequency ω ; the radiation angle θ is the angle between the Poynting vector $\vec{S}$ (i.e., power flow density) and $\vec{v}$. Figure 1a shows multiple wave fronts equally-distributed in phase and with different radii around a stationary source. Note that in negative refractive-index systems, the circular wave fronts propagate inward toward the source (while the wave energy propagates outward instead). So an observer will firstly receive wave fronts with smaller radii before wave fronts with larger radii arrive. When the source moves with a velocity of $v < 2|v_p|$, as in Figure 1b,c, the wave fronts bunch together at $\theta = 180^\circ$ or in the backward direction, where v_p is the phase velocity of light. This leads to an inversed Doppler frequency shift, i.e., $\Delta\omega > 0$ at $\theta = 180^\circ$ in negative refractive-index systems. In contrary, when the source moves with a velocity of $v > 2|v_p|$ in Figure 1d, the wave fronts spread out at $\theta = 180^\circ$, giving rise to the normal Doppler frequency shift, i.e., $\Delta\omega < 0$ at $\theta = 180^\circ$ in negative refractive index systems. It is worthy to note that when the source moves at a subluminal velocity ($v < |v_p|$), as in Figure 1b, an observer at $\theta = 180^\circ$ will firstly receive wave fronts with smaller radii, the same as Figure 1a. In contrast,

if the source moves at a superlight velocity ($v > |v_p|$), as in Figure 1c,d, an observer at $\theta = 180^\circ$ will firstly receive wave fronts with larger radii.

To facilitate the discussion of Doppler effects in the system with a negative refractive-index, we proceed to their analytical derivation. With the application of plane wave expansion [20,29], we have

$\begin{bmatrix} \bar{k} \\ \omega/c \end{bmatrix} = \begin{bmatrix} \bar{\alpha} & +\gamma\bar{\beta} \\ +\gamma\bar{\beta} & \gamma \end{bmatrix} \begin{bmatrix} \bar{k}' \\ \omega_0/c \end{bmatrix}$ from the Lorentz transformation [30]; $\bar{k} = \hat{x}k_x + \hat{y}k_y + \hat{z}k_z$ ($\bar{k}' = \hat{x}k'_x + \hat{y}k'_y + \hat{z}k'_z$) is the wavevector in the laboratory frame (the moving source frame), respectively; $\bar{\beta} = \bar{v}/c$; $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor; $\bar{\alpha} = \bar{I} + (\gamma - 1) \frac{\bar{\beta}\bar{\beta}}{\beta^2}$; $\bar{I}$ is the unity dyad and $\bar{\beta}\bar{\beta} = \hat{z}\hat{z}v^2/c^2$ is also a dyad. From the Lorentz transformation, we can directly have the following two relationships, namely $\omega = \gamma\omega_0 + \gamma vk'_z$ and $k_z = \frac{\gamma v}{c} \cdot \frac{\omega_0}{c} + \gamma k'_z$. By combining these two equations, then it is straightforward to obtain $k_z = \frac{\omega - \omega_0/\gamma}{v}$. Moreover, the relation between k_z and $\bar{k}$ indicates that

$$k_z = n(\omega) \frac{\omega}{c} \cdot \cos\theta \quad (1)$$

where $n(\omega)$ is the refractive index as seen in the stationary laboratory frame. Here we focus on the discussion of the cases with $n(\omega) < 0$, and the Poynting vector $\bar{S}$ is antiparallel to the wavevector $\bar{k}$ in negative refractive-index systems. With the combination of the two equations for k_z , we have

$$\omega - \frac{\omega_0}{\gamma} = n(\omega) \frac{v}{c} \omega \cdot \cos\theta \quad (2)$$

If $n(\omega) \frac{v}{c} \cos\theta \neq 1$ and $\omega_0 \neq 0$ (e.g., the source is a moving dipole), the Doppler effect [21-23,26,31,32] is governed by

$$\omega = \frac{\omega_0/\gamma}{1 - n(\omega) \frac{v}{c} \cos\theta} \quad (3)$$

The appearance of γ in equation (3) is due to the time dilation [30]. Note that equation (3) is applicable to describe the Doppler effect in systems with arbitrary complex value of $n(\omega)$. In equation (3), if $\theta < 90^\circ$

($\theta > 90^\circ$), ω stands for the frequency of waves in the laboratory frame *emitted* by the moving source when the observer lies ahead (behind) of the source.

If $n(\omega)\frac{v}{c}\cos\theta = 1$, equation (3) is satisfied only if $\omega_0 = 0$ (namely the source is a moving charged particle, instead of a moving dipole for the Doppler effect). This corresponds to the backward Cherenkov radiation [1,17-20] and is featured by a backward Cherenkov cone, where its opening angle θ_{CR} satisfies $v\cos\theta_{CR} = c/n$.

Although the Doppler effect and backward Cherenkov radiation in negative refractive-index systems are two different physical phenomena, they have a strong connection via the backward Cherenkov cone. In a nutshell, the backward Cherenkov cone divides the K-space of the Doppler effect into two parts, each of which has different properties. This can be understood as follows.

If $\theta < \theta_{CR}$, equation (3) is valid only for $\omega > 0$, since $n(\omega)\frac{v}{c}\cos\theta < 1$; this corresponds to the conventional inverse Doppler effect in negative refractive-index systems as proposed by Veselago [1]. Namely, the Doppler frequency shift outside the backward Cherenkov cone is always inversed in negative refractive-index systems [Figure 2]. To be specific, the observer will receive a frequency higher (lower) than the emitted frequency during the recession (approach), i.e., $\Delta\omega > 0$ at $\theta > 90^\circ$ ($\Delta\omega < 0$ at $\theta < 90^\circ$) [Figure 1], where $\Delta\omega = |\omega| - \omega_0/\gamma$ is the Doppler frequency shift.

In contrast, if $\theta > \theta_{CR}$, equation (3) is valid only for $\omega < 0$, since $n(\omega)\frac{v}{c}\cos\theta > 1$. The negative ω was firstly revealed by Ginzburg and Frank's theory of superlight Doppler effects in positive refractive-index systems [21-23]. There are many other exotic phenomena related to negative frequencies [33-37], such as the fiber-optical analog of the event horizon [36,37]. Therefore, if $n(\omega)\frac{v}{c}\cos\theta > 1$, equation (3) corresponds to the superlight Doppler effects in negative refractive-index systems. By following Ginzburg and Frank's terminology [22,23], we denote the cone in the K-space satisfying $n(\omega)\frac{v}{c}\cos\theta = 1$ in negative refractive-index systems as the backward Cherenkov cone [Figure 2]. If the frequency dispersion

is neglected, i.e., $n(\omega)$ is a constant, ω diverges and transits from positive infinity to negative infinity when crossing the backward Cherenkov cone. In practical systems with an effective negative refractive index, $n(\omega)$ always has a complex value; this way, the infinity for ω in equation (3) would disappear.

Inside the backward Cherenkov cone, the superlight Doppler effects in negative refractive-index systems can be divided into two types. If $2 > n(\omega) \frac{v}{c} \cos \theta > 1$ in equation (3), the Doppler frequency shift inside the backward Cherenkov cone is still inversed, i.e., $\Delta\omega > 0$ at $\theta > 90^\circ$ [Figure 2]. This is denoted as the superlight *inverse* Doppler effect in negative refractive-index systems.

If $n(\omega) \frac{v}{c} \cos \theta > 2$ in equation (3), we find an un-reported Doppler phenomenon inside the backward Cherenkov cone. To be specific, the Doppler frequency shift in negative refractive-index systems becomes normal in a regime inside the backward Cherenkov cone, i.e., $\Delta\omega < 0$ at $\theta > 90^\circ$ [Figure 2]. This corresponds to the superlight *normal* Doppler effect in negative refractive-index systems. In addition, we show more analyses of the K-space representation of the Doppler effect at different values of v in Supporting Information Figure S3.

To facilitate the potential observation of the revealed normal Doppler frequency shift in Figures 1 and 2, a realistic negative refractive-index system is needed. Ever since the advent of metamaterials, the negative refractive-index systems have attracted enormous attentions [2-6,8,9,19,38]. In Veselago's seminal work [1], a negative refractive-index system refers to a material with simultaneously negative permittivity and permeability. Such a double negative material does not naturally exist but can be artificially constructed, such as through the design of metamaterials [38] and photonic crystals [8,39], but its realization is generally challenging. In addition to double negative materials, the effective negative refractive index for eigenmodes in some plasmonic or waveguide systems have also been reported, if the directions of the phase and group velocities for these eigenmode are anti-parallel (this circumvents the requirement for the permittivity and permeability to be simultaneously negative). For example, the effective negative refractive index has been realized for highly squeezed polaritons, e.g., metal plasmons in a metal-insulator-metal

structure as shown in Figure 3 [27,28] and phonon polaritons in a thin slab of hexagonal boron nitride [40-43].

Before we proceed, it shall be emphasized that the analytical derivation for the Doppler effect in equations (1-3) is also applicable to plasmonic or waveguide systems, if they support eigenmodes propagating in a plane parallel to the source's trajectory (e.g., waves guided in the x - z plane but confined along the y direction) and if these eigenmodes have an effective negative refractive index $n_{\text{eff}}(\omega)$. In such systems, the Poynting vector $\vec{S}$ becomes antiparallel to the in-plane wavevector $\vec{k}_{||} = \hat{x}k_x + \hat{z}k_z$ (the component parallel to the x - z plane) of these eigenmodes and the effective in-plane refractive index is defined as $n_{\text{eff}}(\omega) = k_{||}/(\omega/c)$. For plasmonic systems such as metal plasmons in the metal-insulator-metal structure [27,28], $\vec{k}_{||} = \vec{k}_{\text{spp}}$, where $\vec{k}_{\text{spp}}$ is the in-plane wavevector of plasmonic eigenmodes. Accordingly, for plasmonic or waveguide systems, $n(\omega)$ in equations (1-3) shall be replaced with $n_{\text{eff}}(\omega)$, and θ becomes the angle between $\vec{S}$ (or $-\vec{k}_{||}$) and $\vec{v}$; see the inset of Figure 4 for example.

From equation (3) and the above analysis, the deterministic factor for the Doppler effect is the effective refractive index, instead of the effective permittivity or permeability. Therefore, it is feasible to adopt some plasmonic or waveguide systems, which support the propagation of eigenmodes with an effective negative refractive index, to demonstrate the superlight normal Doppler effect in Figures 1 and 2. As a typical example, the negative refractive-index metal plasmons are adopted in the following discussions.

Figure 3 shows the dispersion of metal plasmons in a metal-insulator-metal structure. For metal plasmons in this plot, we pre-set the value of their group velocity $v_g = \frac{\partial \omega}{\partial k_{\text{spp}}}$ to be positive, i.e., $v_g > 0$, to facilitate the clear definition of their effective refractive index. Correspondingly, the phase velocity for metal plasmons is $v_p = \frac{\omega}{k_{\text{spp}}}$. If the directions of the phase and group velocities are anti-parallel in the x - z plane, we have $v_g \cdot v_p < 0$ and thus $v_p < 0$. Since $v_p < 0$, we have $\text{Re}(k_{\text{spp}}) < 0$ if $\omega > 0$ in Figure 3. This way, the effective refractive index of metal plasmons can be directly defined as $n_{\text{eff}}(\omega) = k_{\text{spp}}/(\omega/c)$. From

the principle of causality and the fact that all electromagnetic fields in time domain are real-valued, we also have $n_{\text{eff}}(-\omega) = n_{\text{eff}}^*(\omega)$ [30]. In Figure 3, the experimental data of permittivity of silver [44] is adopted. The insulator has a refractive index of 3 (e.g., boron phosphide [45]) and a thickness of $d = 0.01\lambda_p$, where $\lambda_p = 300$ nm. Figure 3 shows that $n_{\text{eff}}(\omega)$ for metal plasmons is negative within the range of $[0.6 \text{ } 0.9]\omega_p$, where $\omega_p = 2\pi/\lambda_p$. Moreover, it is noted that for negative refractive-index systems, the absolute value of refractive index generally decreases with the frequency, such as metal plasmons in Figure 3.

Figure 4 shows the possible realization of the normal Doppler frequency shift for the negative refractive-index metal plasmons. Below we consider the working frequencies only in the above range and let the dipole move parallel to the interfaces of metal-insulator-metal; see the structural setup in the inset of Figure 3. Note that the vertical distance between the moving dipole and the interface of metal-insulator-metal has a trivial influence on the Doppler frequency shift in Figure 4, although it may affect the field distribution of excited metal plasmons. Two cases, i.e., $v = 0.08c$ and $v = 0.8c$, are studied in Figure 4. It shall be emphasized that the frequency dispersion of negative refractive-index systems is neglected for conceptual demonstration only in Figures 1 and 2 and also in Veselago's seminal work [1], but is unavoidable in reality [46] such as the realistic system in Figures 3 and 4. When considering the dispersion, we note that the Doppler effect in negative refractive-index systems will be highly dependent on the dispersion. For example, due to the specific dispersion of metal plasmons (where $|n_{\text{eff}}(\omega)|$ decreases with frequency), there are two unique phenomena related to the superlight normal Doppler effect in negative refractive-index systems.

First, the superlight normal and conventional inverse Doppler effects for negative refractive-index metal plasmons may simultaneously show up at the same values of θ in Figure 4. For example, when $v = 0.08c$ in Figure 4, we simultaneously have $\omega = 0.96\omega_0/\gamma$ (which corresponds to the superlight normal Doppler effect in negative refractive-index systems) and $\omega = 1.21\omega_0/\gamma$ (conventional inverse Doppler effect in negative refractive-index systems) at $\theta = 150^\circ$. This phenomenon can be explained as follows. When considering the dispersion in negative refractive-index systems, the backward Cherenkov cone in the

interested frequency range can still be well defined as the cone in the K -space that has the minimum value of θ satisfying $n_{\text{eff}}(\omega) \frac{v}{c} \cos \theta = 1$. According to the definition of the backward Cherenkov cone in dispersion-less and dispersive systems, the superlight Doppler effects in negative refractive-index systems always appear inside the backward Cherenkov cone. In contrast, the conventional inverse Doppler effect in negative refractive-index systems appears only outside the backward Cherenkov cone when the dispersion is neglected as in Figure 2 but may appear inside the backward Cherenkov cone when the frequency dispersion is considered as in Figure 4. In other words, when considering the frequency dispersion, the superlight Doppler effects and the conventional inverse Doppler effect in negative refractive-index systems may be partially overlapped in the K -space inside the backward Cherenkov cone, as shown in Figure 4.

Second, the superlight normal Doppler effect might have even a lower velocity threshold than the superlight inverse Doppler effect. In absence of the frequency dispersion, one shall always expect that, the appearance of superlight normal Doppler effect (which requires $v > 2c/|n|$ from equation (3)) always has a larger threshold of v than the superlight inverse Doppler effect (which only needs $v > c/|n|$ from equation (3)); see more analysis in Supporting Information Figure S3. As a result, inside the backward Cherenkov cone in Figure 2, the regime of superlight normal Doppler effect should be always wrapped around by the regime of superlight inverse Doppler effect. However, this rule is not applicable when considering the realistic dispersion of negative refractive-index systems. As a representative example, when $v = 0.08c$ in Figure 4, for superlight Doppler effects of negative refractive-index metal plasmons, there is only the superlight normal Doppler effect, without the appearance of the superlight inverse Doppler effect. To facilitate the explanation of this example, we choose two frequencies of ω_{low} and ω_{high} in the neighborhood of ω_0/γ , and let $|\omega_{\text{low}}| < \omega_0/\gamma < |\omega_{\text{high}}|$. For metal plasmons with $|n_{\text{eff}}(\omega)|$ decreasing with frequency, one has $|n_{\text{eff}}(\omega_{\text{low}})| > |n_{\text{eff}}(\omega_{\text{high}})|$, which may lead to $c/|n_{\text{eff}}(\omega_{\text{high}})| > v > 2c/|n_{\text{eff}}(\omega_{\text{low}})|$ [e.g., when $|n_{\text{eff}}(\omega_{\text{low}})| > 2|n_{\text{eff}}(\omega_{\text{high}})|$]. If $c/|n_{\text{eff}}(\omega_{\text{high}})| > v > 2c/|n_{\text{eff}}(\omega_{\text{low}})|$, we can have the situation that the emergence condition of superlight normal Doppler effect (i.e., $v > 2c/|n_{\text{eff}}(\omega_{\text{low}})|$) is fulfilled, while the emergence condition of superlight inverse Doppler effect ($v >$

$c/|n_{\text{eff}}(\omega_{\text{high}})|$) is failed. In other words, when considering the realistic dispersion, the appearance of superlight normal Doppler effect does not always need to have a larger threshold of v than the superlight inverse Doppler effect in negative refractive-index systems.

By using the second feature of the superlight normal Doppler effect in Figure 4, we show in Figure 5 the possibility to spatially separate the superlight normal Doppler effect from the other Doppler effects in negative refractive-index systems, which may facilitate its experimental observation. Consider that a circularly-polarized source, moves along the $+\hat{z}$ direction and has a dipole moment of $\bar{P}(\bar{r}', t') = \text{Re}\{(\hat{x} + \hat{y}i)e^{-i\omega_0 t'}\}\delta(\bar{r}')$ in the moving source frame. Figure 5 shows the distribution of emitted plasmons in the time domain with $v = 0.08c$. Two asymmetric caustics [47,48] are formed in regions $x > 0$ and $x < 0$ and propagate to the backward direction. For the excited metal plasmons dominant at region $x < 0$, they propagate along the backward direction and have their wavelength much smaller than the plasmonic wavelength at ω_0/γ ; from Figure 3, this indicates that the excited metal plasmons have their frequency smaller than ω_0 , i.e., $|\omega| < \omega_0/\gamma$. In other words, the frequency of the excited metal plasmons along the backward direction in region $x < 0$ is red shifted. As such, region $x < 0$ corresponds to the superlight normal Doppler effect for negative refractive-index metal plasmons. For the excited metal plasmons dominant at region $x > 0$, they also propagate along the backward direction but have their wavelength much larger than the plasmonic wavelength at ω_0/γ ; then from Figure 3, we have $|\omega| > \omega_0/\gamma$ for the excited metal plasmons at region $x > 0$. In other words, the frequency of excited metal plasmons along the backward direction in region $x > 0$ is blue shifted, and hence region $x > 0$ corresponds to the conventional inverse or superlight inverse Doppler effects. From Figure 4, there is no superlight inverse Doppler effect of metal plasmons in the studied frequency range for the case of $v = 0.08c$. As a result, region $x > 0$ in Figure 5 is dominated by metal plasmons having the conventional inverse Doppler effect.

Last but not least, it is worthy to note that the Doppler effect has wide applications in various realms including the laser cooling [49], the tunable control of the transition frequency of semiconductor emitters

[50], and the design of plasmonic Doppler gratings for azimuthal angle resolved nanophotonic applications such as color sorters or refractive index sensors [51,52]. Then the revealed phenomenon of superlight Doppler effects in negative refractive-index systems may enrich these useful applications, as well as the exploration of non-locality in photonics and plasmonics.

3. Conclusion

In conclusion, we have revealed the possibility to create the normal Doppler frequency shift in negative refractive-index systems, by finding an un-reported superlight normal Doppler effect in a regime inside the backward Cherenkov cone. This way, our work further develops Veselago's theory of inverse Doppler effect in negative refractive-index systems and Ginzburg & Frank's theory of superlight Doppler effects in positive refractive-index systems. In addition to the isotropic (for both negative and positive refractive-index) systems, there are many other anisotropic systems, such as systems supporting hyperbolic eigenmodes (e.g., hyperbolic metamaterials) and photonic or plasmonic systems supporting nonreciprocal eigenmodes. The continuing exploration of Doppler effects at different velocities of the moving source in these intriguing systems [53,54] is highly wanted.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords:

Doppler effect, Cherenkov radiation, negative refraction, surface plasmons, metamaterials

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Figure 1. Real-space illustration of normal Doppler frequency shifts in a negative refractive-index system. The multiple wave fronts, illustrated by circular lines, are equally-distributed in time. A source or dipole moves with a velocity $\bar{v} = \hat{z}v$. In the moving source frame, the source has a natural frequency ω_0 . In the laboratory frame, the received radiation fields have a frequency ω ; θ is the angle between Poynting vector $\bar{S}$ and $\bar{v}$ (or the $\hat{k}_z$ axis); γ is the Lorentz factor and is different in each panel. **a** If $v = 0$, there is no Doppler frequency shift, i.e., $\Delta\omega = 0$, where $\Delta\omega = |\omega| - \omega_0/\gamma$. **b, c** If $v < 2|v_p|$, the wave fronts bunch together at $\theta = 180^\circ$, where $v_p = c/n$ is the phase velocity of light. This leads to an inverse Doppler frequency shift, i.e., $\Delta\omega > 0$ at $\theta = 180^\circ$. **d** If $v > 2|v_p|$, the wave fronts spread out at $\theta = 180^\circ$, leading to a normal Doppler frequency shift, i.e., $\Delta\omega < 0$ at $\theta = 180^\circ$. Here we set n to be a negative constant with $n < -2.5$ for illustration.

Figure 2. K-space representation of the normal Doppler frequency shift in negative refractive-index systems. The normal Doppler frequency shift can appear in a regime (blue region) inside the backward Cherenkov cone. In the laboratory frame, the received radiation fields have a wavevector $\bar{k}$; the corresponding Poynting vector (i.e, the power flow density) $\bar{S}$ is antiparallel to $\bar{k}$; θ is the angle between $\bar{S}$ and $\bar{v}$. The angles of θ_{SDE} and θ_{SNDE} are the opening angles of the cone in which the superlight Doppler effects (blue and orange regions) occur and of the cone in which the superlight normal Doppler effect occurs, respectively. Note that $\theta_{SDE} = \theta_{CR}$, where θ_{CR} is the opening angle of the backward Cherenkov cone created by a moving charged particle (instead of a dipole here), since both θ_{SDE} and θ_{CR} satisfy the condition of $v \cos \theta = c/n$. For the conceptual illustration, we let $v > 2c/|n|$ and set n to be a negative constant here.

Figure 3. Dispersion of negative refractive-index metal plasmons in a metal-insulator-metal structure. For metal plasmons, $\bar{k}_{\text{spp}} = \hat{x}k_x + \hat{z}k_z$ is the component of wavevector parallel to the x - z plane or the interface. This figure is plotted by setting the group velocity of metal plasmons to be positive, i.e., $\frac{\partial \omega}{\partial \text{Re}(k_{\text{spp}})} > 0$. This way, the effective refractive index of metal plasmons can be defined as $n_{\text{eff}}(\omega) = k_{\text{spp}}/(\omega/c)$. The real part of $n_{\text{eff}}(\omega)$ is negative and its absolute value *decreases* with frequency, when the frequency is within the range of $[0.6 \ 0.9]\omega_p$, where $\omega_p = 2\pi/\lambda_p$ and $\lambda_p = 300$ nm. For the negative refractive-index metal plasmons, we have $\text{Re}(k_{\text{spp}}) \cdot \text{Im}(k_{\text{spp}}) < 0$; in other words, k_{spp} is in the second or fourth quadrant of the complex k_{spp} plane. The metal-insulator-metal structure is shown in the inset. The experimental data of permittivity of silver [44] is adopted. The insulator has a refractive index of 3 (e.g., boron phosphide [45]) and a thickness of $d = 0.01\lambda_p$.

Figure 4. Normal Doppler frequency shift of negative refractive-index metal plasmons in a metal-insulator-metal structure. The Doppler frequency shift is normal in the blue regions (namely $\Delta\omega < 0$ at $\theta > 90^\circ$ and $\Delta\omega > 0$ at $\theta < 90^\circ$), but is inversed in the yellow regions ($\Delta\omega > 0$ at $\theta > 90^\circ$ and $\Delta\omega < 0$ at $\theta < 90^\circ$). A dipole moves parallel to the interface of the meta-insulator-metal structure and excites metal plasmons. The propagating angle θ for excited metal plasmons in the x - z plane is illustrated in the inset; the corresponding structural setup is shown in the inset of Figure 3. The dipole moves with a velocity $\vec{v} = \hat{z}v$ and has $\omega_0 = 0.75\omega_p$, where $\omega_p = 2\pi/\lambda_p$ and $\lambda_p = 300$ nm. The effective refractive index for metal plasmons is negative, e.g., $n(0.75\omega_p) = -22$, and decreases with frequency in the studied frequency range; see Figure 3. The normal Doppler frequency shift of metal plasmons can appear if $v = 0.08c$, i.e., the superlight normal Doppler effect with $\Delta\omega < 0$ at $\theta > 90^\circ$.

Figure 5. Real-space representation of the superlight normal Doppler effect spatially separated from the other Doppler effects for the negative refractive-index metal plasmons. A circularly-polarized dipole source with $\omega_0 = 0.75\omega_p$ moves with a velocity $\vec{v} = \hat{z}v$, where $v = 0.08c$. The distribution of the asymmetric radiation fields of metal plasmons at a fixed time $t = t_0$ (when the source is at $z = 1.7 \mu\text{m}$) is shown here. Region $x < 0$ is dominated by the superlight normal Doppler effect. Region $x > 0$ is dominated by the conventional inverse Doppler effect. The vertical distance between the source and the neighboring silver-insulator interface (at which the radiation fields are plotted) is $y = 10 \text{ nm}$. The structural setup of silver-insulator-silver is the same as Figure 3.