the optical axis in the metamaterial space, thus the image is always virtual and inverted. Depending on the relative position of the object, the image may be different in size; when the object is outside the first but inside the second focal length, i.e., $f_m < v_m < 2f_m$, the image is magnified, as shown in Fig. 4(c); when the object is at the second focal length, i.e., $v_m = 2f_m$, the image has the same size as the object, as shown in Fig. 4(e); when the object is outside the second focal length, i.e., $v_m > 2f_m$, the image is minified, as shown in Fig. 4(g). All the four cases above for an object in the metamaterial are numerically verified, as shown in Fig. 4(b)-(h). These extraordinary properties of a hyperbolic metalens are summarized in Table 2, which can also be directly derived from the metalens imaging equations (Eq. (2) and (3)).

Table 2. Imaging Properties of a Hyperbolic Metalens. f_m>0 and f_d < 0.

Object	Image			
Location	Type	Location	Orientation	Relative size
$\infty > v_d > 0$	Real	$0 < v_m < f_m$	Erect	Minified
$\infty > v_m > 2f_m$	Virtual	$2f_d < v_d < f_d$	Inverted	Minified
$v_m = 2f_m$	Virtual	$v_d = 2f_d$	Inverted	Same size
$f_m < v_m < 2f_m$	Virtual	$-\infty < v_d < 2f_d$	Inverted	Magnified
$v_m = f_m$		$\pm\infty$		
$v_m < f_m$	Real	$0 < v_d < \infty$	Erect	Magnified

As shown in Fig. 3 and Fig. 4, the magnification of the metalens can also be determined analytically through the transverse magnification M_T

$$M_T = \frac{u_m}{u_d} = -\frac{g_m}{f_m} = -\frac{f_d}{g_d} \tag{4}$$

where u_m and u_d are the object/image height, i.e., the distance from the object/image to the optical axis, in the metamaterial and air space respectively; g_m and g_d are the object/image distance reckoned from their focus in the metamaterial and air space respectively.

4. Discussions and conclusions

Although illustrated using hyperbolic metalenses with f_m>0, f_m can also be designed to be negative (f_m<0), meaning a plane wave from the air side diverges in the hyperbolically dispersive metamaterial. In this case, a plane wave from the metamaterial side will be focused in air, resulting in a positive f_d. Analyses show that all the above equations remain valid and the hyperbolic metalens with f_m<0 is also a "Janus lens". The imaging properties of such a hyperbolic metalens with f_m<0 can also be deduced through a similar method mentioned above.

We finally emphasize that the new set of imaging properties in the exampled hyperbolic metalens is a result of the hyperbolic dispersion of the metamaterials. The hyperbolic metalenses also possess super resolution capabilities as demonstrated before [23, 24]. The rules are applicable to any other type of phase compensated lenses that experiences negative refraction at the air/lens interface. These exotic imaging properties are impossible to realize by conventional lenses, thus extending the imaging properties and the capabilities of lenses, and the imaging optics in general, to a new horizon. A practical usage of such lenses is to truncate the metamaterial to the focal/image plane so that the optical near field can be accessed from air [29]. The new found imaging behaviors and the super resolving power of hyperbolic metalenses provide new opportunities to explore novel optical devices and systems and will profoundly affect the advancement of optics.

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