Abstract—Chiral mirrors are a class of metamaterials that reflect circularly polarized light of a certain helicity in a handedness-preserving manner, while absorbing circular polarization of the opposite handedness. However, most absorbing chiral mirrors operate only in a narrow frequency band, as limited by the causality principle. Instead of absorbing the undesired wavefront, here we propose a transparent chiral mirror that allows undesired waves to pass through. In particular, the handedness-preserving band of the transparent chiral mirror is free of the causality limit, thus enabling broadband functionality. Furthermore, since electromagnetic waves outside the handedness-preserving band may transmit through the proposed chiral mirror, the reflected wave contains only circular polarization components of a certain handedness over a wide frequency range, which is favored in many applications. Moreover, the scheme is lossless and scalable. To realize the proposed transparent chiral mirror, we apply an array of helical microstructures in a two-dimensional square lattice. Traditionally, this kind of structure has been used as a circular polarizer but we apply it instead in a reflective mode. Our work provides a bandwidth analysis of chiral mirrors, and paves the way to new opportunities for creating broadband chiral metamaterials with handedness-preserving properties.

Index Terms—Absorption, bandwidth limit, broadband, circular polarization, chiral mirror, metamaterial.

I. INTRODUCTION

Artificial chiral structures, especially those in the emerging field of chiral metamaterials, have been highly effective for applications involving polarization selectivity [1], [2]. Researchers have realized a variety of two- and three-dimensional chiral metamaterials composed of structures that are non-superimposable on their own mirror image, giving rise to a series of applications in polarization manipulation, imaging, chemical and biological detection, and nonlinear optics [3]–[10].

Conventional mirrors will reverse the handedness of circularly polarized electromagnetic waves upon reflection (Fig. 1a). This holds true for both simple “electric mirrors” and metamaterial-based “magnetic mirrors” [11]–[13], which reverse the direction of the reflected electromagnetic wave’s electric and magnetic field, respectively. To preserve the handedness of the reflected wave [14], Eric and Nikolay proposed a type of chiral mirror [15] (Fig. 1b). In the handedness-preserving band, the mirror reflects one circular polarization without changing its handedness while absorbing the other. This type of chiral mirror brings new functionalities that go beyond the conventional mirrors [16]–[21].

However, these absorbing chiral mirrors suffer from a narrow handedness-preserving band [22], because the absorption bandwidth of any passive layer with a fixed thickness is limited by the causality principle [23]. To design a broadband chiral mirror requires a different design methodology.

II. DESIGN METHODOLOGY

Other than traditional absorbing schemes, a matching technique can also be employed to transmit unwanted waves without reflection. Moreover, a matching technique has no limitation according to the causality principle, and thus has the potential to operate over a much wider bandwidth [24]. As shown in Fig. 1, both the absorbing (Fig. 1 (b), (c)) and matching (Fig. 1 (d), (e)) methods are capable of meeting the goal of low reflection for the undesirable handedness [25]. It is seen that the transparent chiral mirror exhibits the same handedness-preserving reflection property as conventional chiral mirrors. In other words, only left-handed or right-handed circularly polarized waves (LCPs or RCPs) of a certain handedness are reflected without handedness flipping. Therefore, exploitation of a transparent chiral mirror, which transmits the undesired polarization instead of absorbing it, provides a new design methodology for achieving a broadband handedness-preserving response.

While most existing work has focused strictly on the response inside the handedness-preserving band, here we also consider the out-of-band performance. Most chiral mirrors to date include an impenetrable metal ground plane backing, which reflects all waves both inside and outside of the handedness-preserving band. Figure 2 demonstrates the wideband responses of a conventional mirror, an absorbing chiral mirror and the proposed transparent chiral mirror. For the traditional absorbing chiral mirror, the frequency band of...
reflected waves with mixed polarizations is very close to the handedness-preserving band, and thus it is difficult to filter them out, as shown in Fig. 2 (b). On the contrary, for transparent chiral mirrors, the mixed polarizations can be easily filtered out, as shown in Fig. 2 (c). Consequently, if it is desired to use circular polarization of a certain handedness (LCP or RCP), the reflected wave of the transparent chiral mirror possesses high polarization purity compared to traditional absorbing chiral mirrors, making it more attractive for many applications.

III. BANDWIDTH ANALYSIS

This section develops the theoretical foundation for the narrowband limitation of the conventional absorbing chiral mirror, as well as the broadband handedness-preserving response of the proposed transparent chiral mirror. For chiral materials, the reflected and transmitted field may be written as [26]:

\[ E_r = -\frac{j\omega}{2S} \left[ (\eta \hat{\alpha}_{ee}^{co} + \hat{\alpha}_{em}^{cr} + \hat{\alpha}_{me}^{co} - \frac{1}{\eta} \hat{\alpha}_{mm}^{co}) \vec{I}_t + \left( \eta \hat{\alpha}_{ee}^{cr} - \hat{\alpha}_{em}^{co} - \hat{\alpha}_{me}^{cr} - \frac{1}{\eta} \hat{\alpha}_{mm}^{cr} \right) \vec{I}_t \right] \cdot E_{inc} \]

\[ E_t = \left\{ 1 - \frac{j\omega}{2S} \left[ (\eta \hat{\alpha}_{ee}^{cr} + \hat{\alpha}_{em}^{co} + \frac{1}{\eta} \hat{\alpha}_{me}^{co} + \frac{1}{\eta} \hat{\alpha}_{mm}^{co}) \vec{I}_t \right] \right\} \cdot E_{inc} \]

where \( \omega \) is the angular frequency, \( S \) is the area size of the metamaterial, \( \eta \) is the wave impedance, \( \vec{I}_t \) and \( \vec{I}_t \) are the unit dyadic and the transverse rotation dyadic, respectively. The "\( e \)" components are the effective polarizabilities of electric(e) and magnetic(m) fields, respectively. The index "\( co \)" stands for co-polarization, while the index "\( cr \)" stands for cross-polarization. For simplicity, here we only consider a chiral mirror’s response when illuminated by a normally incident linearly polarized plane wave propagating in \(-z_0\) direction. Linearly polarized waves can be considered as a mixture of LCP and RCP waves. However, only one specific handedness of a CP wave is reflected by a chiral mirror. Hence, the reflection properties are governed by the relationship:

\[ \eta \hat{\alpha}_{ee}^{co} + \hat{\alpha}_{em}^{cr} + \hat{\alpha}_{me}^{co} - \frac{1}{\eta} \hat{\alpha}_{mm}^{co} = (\pm j) \left( \eta \hat{\alpha}_{ee}^{cr} - \hat{\alpha}_{em}^{co} - \hat{\alpha}_{me}^{cr} - \frac{1}{\eta} \hat{\alpha}_{mm}^{cr} \right) \]

Here the coefficient \( \pm j \) correspond to LCP and RCP waves reflected by a left- and right-handed chiral mirror, respectively. Equation (3) is a necessary condition that applies in general to all types of chiral mirrors. From (3) it can be concluded that the effective polarizabilities are frequency independent, which suggests the broadband handedness-selective reflecting potential of chiral mirrors.

However, conventional absorbing chiral mirrors require the transmission to be zero. Thus, (3) can be used to derive the following relationship:

\[ \left\{ \begin{array}{l} \eta \hat{\alpha}_{ee}^{co} + \hat{\alpha}_{em}^{cr} - \frac{1}{\eta} \hat{\alpha}_{mm}^{co} = \frac{2s}{j\omega} \\ \eta \hat{\alpha}_{ee}^{cr} - \hat{\alpha}_{em}^{co} + \frac{1}{\eta} \hat{\alpha}_{mm}^{cr} = 0 \end{array} \right. \]
is capable of realizing the proposed transparent chiral mirror with properties described in the above sections. One well known type of chiral metamaterial unit cell is the metallic helix. This structure has been commonly used in circular polarizers, which transmit only circular polarization of a certain handedness in its operating band [27]–[30]. Although Justyna et al. observed that the untransmitted circular polarization is reflected rather than absorbed [30], most circular polarizer designs focus solely on the transmitted chiral properties and ignore the reflection.

Figure 3(a) shows the unit cell geometry of the proposed broadband transparent chiral mirror. A helical structure with two turns is chosen to achieve a broadband chiral response [30]. The analytical expression that describes the helical wire geometry is:

\[
\begin{align*}
    x &= 8 \cos(\pi t) \\
    y &= 8 \sin(\pi t) \\
    z &= 10t - 20
\end{align*}
\]

where \( t \) varies from 0 to 4, and all units are in millimeters. These helical wires have a radius of 1 mm, arranged in a 22 mm \( \times \) 22 mm two-dimensional square lattice. The reflection and transmission, shown in Fig. 3(b) and Fig. 3(c) respectively, exhibit a broad handedness-preserving band, where LCP waves are reflected while RCP waves are transmitted. The in-band reflective behavior is similar to that of absorbing chiral mirrors, but with a much broader bandwidth.

The proposed transparent chiral mirror comprised of helical elements was simulated in the frequency domain with Floquet boundary conditions using the Computer Simulation Technology (CST) software package. The percentage bandwidth of the left-handed-preserving band is more than 80%, which is much wider than the conventional absorbing chiral mirrors reported in the literature.

Fig. 3 (b) also depicts the response outside of the handedness-preserving band. It shows that the reflected waves with mixed polarizations are separate from the desired RCP band, thus they are much easier to filter out, enabling high polarization purity of reflected RCP waves.

Moreover, for the transmission shown in Fig. 3(c), we observe that a RCP transparent chiral mirror could also be used here as a left-handed circular polarizer. This observation indicates that, with the same structure, many conventional circular polarizers can also be employed as transparent chiral mirrors, depending on whether transmitted or reflected circular polarization is desired.

V. CONCLUSION

In this paper, we studied the fundamental bandwidth limit of a conventional absorbing chiral mirror, and proposed a broadband transparent chiral mirror that is free of such a limitation. We introduced a possible way to realize chiral mirrors with better handedness-preserving bandwidth by transmitting the unwanted circular polarization component instead of absorbing it. Such a scheme has less restriction on the performance.

IV. DESIGN AND VERIFICATION

Fortunately, we do not have to look far to find a structure that
can be positioned separate from the desired handedness-preserving band and are easily filtered out, rendering high polarization purity. To realize the functionalities of such transparent chiral mirrors, we pointed out that arrays of helices, which have been employed in conventional circular polarizers, could also be applied in a reflective manner.

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Fig. 3. (a) Unit cell configuration of an example right-hand transparent chiral mirror. The helices are positioned in a periodic array on a square lattice in the xy-plane. (b) The simulated reflection shows a broad handedness-preserving band. The reflected mixed polarizations are separate from the handedness-preserving band, thus it is easy to filter them out, rendering high polarization purity. (c) The simulated transmission response indicates its capability to perform as a conventional left-handed circular polarizer.
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