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Engineering of Intelligent Reflecting Surfaces: Reflection Locality and Angular Stability

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Abstract—Reconfigurable intelligent surfaces (RISs) are electromagnetically passive controllable structures, deflecting incident wave beams in tunable directions. A usual way to design RIS using metasurfaces (MSs) is based on the approximation in which the reflective properties of a uniform MS are attributed to unit cells of the nonuniform one. We call this approximation the reflection locality (RL) and analyze its applicability. We prove that RL holds for a wide range of incidence and deflection angles if and only if uniform MSs based on which the nonuniform one is generated possess so-called angular stability (AS). AS of an infinite uniform MS (that we call generic MS) means that its reflection coefficient is independent of the incidence angle for both TE and TM polarizations.

Index Terms—Angular stability (AS), channel reciprocity, metasurface (MS), reconfigurable intelligent surface (RIS), smart environment, wireless communication.

I. INTRODUCTION

Recent years have witnessed a remarkable growth in attention toward the transition to high-frequency wireless networks. The reasons are higher peak data rates, more accurate localization of users/objects, and denser connectivity [1], [2], [3]. Frequencies below 10 GHz are not perfect for 5G and 6G cellular networks, since they cannot support the needed data rates and low latency communication as well as virtual/augmented reality, autonomous driving, and the Internet of Things [4]. As optical wireless communications, they suffer from atmospheric absorption, low transmission power budget, and high diffusion losses on surfaces. Therefore, frequencies between 20 GHz and 1 THz are commonly recognized, nowadays, to be optimal for prospective wireless communications [5], [6]. Meanwhile, these communications networks still suffer from obstacles blocking communication paths [5], [6]. To cope with this challenge, the concept of reconfigurable intelligent surfaces (RISs) has been introduced which is based on the phenomenon of anomalous reflection [7], [8], [9], [10]. Anomalous reflection from metasurfaces (MSs) with periodic nonuniformity has been extensively studied since 2011 when paper [7] was published (though its main result called the generalized reflection law was initially revealed long ago, in paper [11]). In the following decade, the idea of controllable anomalous reflection with minimized scattering losses was developed in numerous works (see the review [8]). As a means of enabling future smart wireless networks, the concept of RIS-based wireless communication was proposed, in which the RIS is claimed to be a fully controllable anomalous reflector [9]. After 2019, the development of RISs has become even more extensive (see [1], [2], [3], [4], [9], [10], [12], [13], [14], [15], [16]). An RIS in its modern understanding is a 2-D array of reflecting elements that play the role of an electromagnetically passive but electronically (or optically) tunable relay station between the transmitter and receiver [9], [10], [12]. With advantages such as consuming little power, requiring less hardware complexity, and adapting to dynamic wireless channels, an RIS becomes an ideal candidate for smart radio environments [12]. Several studies have focused on RIS from a variety of points of view, including multimonodulation schemes [13], passive beamforming [14], and MIMO-assisted networks [15].

As it was explained in [10], RISs can be implemented in three ways: as an MS, which is a planar array of deeply subwavelength unit cells, as a meta-grating (where the scattering elements are deeply subwavelength but the gaps between them are substantial), and as a phased array, whose elements have the size close to \( \lambda/2 \) (\( \lambda \) is the wavelength). Each approach has its own advantages and disadvantages, discussed in [9], [10], [17], [18], [19], and [20]. In this article, we concentrate on RISs based on MSs.

The most common method for engineering anomalous reflection by an MS is to engineer its local reflection phase \( \Phi_R \) varying linearly along the trace of the incidence plane [7], [11]. In this method, one assumes that \( \Phi_R(A) \) at any point \( A \) of a nonuniform MS is equal to \( \Phi^A_R \) calculated for a uniform MS, in which all unit cells are the same as that at point \( A \). We call these uniform arrays generic MSs. This approximation is called locally periodic approximation. The reflection locality (RL) property means that for this MS this well known and generally used approximation is adequate. Physically, this means that the current induced at a certain unit cell depends only on
the setting of this unit cell and on the incident field at its location.

It is important to note that the RL approximation is not equivalent to the physical optics (PO) approximation that is defined as the applicability of the ray optics for finding the currents and fields on scattering surfaces (e.g., [21]). RL does not ensure the validity of the PO approximation, and, on the other hand, PO can be in some cases applied to reflectors that do not possess the property of the local response. In this article, we do not study the criteria of applicability of PO.

We study the region of RL assumption validity on the example of periodic nonuniform MSs (PNUMSs) formed by periodically repeated sections of step-wise uniform MSs. In the literature on RISs, the RL approximation for the design of PNUMSs is often used without considering its applicability (see [9], [10], [13], [14], [22], [23], [24]). However, if a PNUMS is dedicated to operating in a regime that is very different from the usual reflection law for uniform reflectors, this approach may result in serious errors. For example, in [24], a varactor-based RIS was engineered assuming RL. The authors deduced that the channel reciprocity will be violated either when the angle of anomalous reflection \( \theta_i \) is large and the incidence angle \( \theta_i \) is small or in the opposite case. However, since all the conditions for the validity of the reciprocity theorem [25] are fulfilled, the response must be reciprocal. Therefore, we conclude that the RL assumption is not valid for that MS. This example shows that using RL without considering its applicability can lead to wrong conclusions about RIS operations.

In this article, we prove the possibility of applying the RL assumption for a certain class of MSs: MSs whose generic (infinite and uniformly loaded) counterparts possess so-called angular stability (AS) of their response. The AS of a uniform infinite MS means that the reflection coefficient of this MS is independent of the incident angle for both orthogonal polarizations. We show that the concept of AS for a uniform MS and the concept of RL for its nonuniform counterpart are equivalent in practical cases of slow spatial variations of the unit cell parameters. The specific example MS considered here possesses AS for both polarizations with a 20% frequency bandwidth, and we show the applicability of RL for it namely in this frequency range.

Next, we numerically and experimentally illustrate this result with two examples of so-called binary MSs. In a binary MS, each half-period comprises identical unit cells which differ in the half-periods only by their lumped loads [26], [27], [28]. Conventionally, binary MSs are designed using the RL assumption. First, one considers uniform MSs with two different unit-cell loads, corresponding to states “0” and “1.” The reflection phases of these two MSs should be nearly opposite: \( \Phi_R^{(0)} - \Phi_R^{(1)} \approx 180^\circ \) [24], [26], [27], [28]. In practice, some phase difference \( \Delta \Phi_R \) in the interval \((180 \pm 40)^\circ\) is still allowed [29]. Second, one applies the RL approach when one half-period of the PNUMS is characterized by the local reflection phase \( \Phi_R^{(0)} \), and another half-period—by the local reflection phase \( \Phi_R^{(1)} \) [24], [26], [27], [28], [29]. Each unit cell of the PNUMS can have one of the two loads, that is, the period is controllable. If RL is applicable, the deflection angle is controllable, too.

In our previous paper [30], we developed a uniform MS possessing AS, and here we use it in studies of the RL approximation validity. The surface consists of a grid of metal Jerusalem crosses located on top of a metal-backed dielectric substrate with very small but not negligible losses. We numerically and experimentally show that the RL is really adequate for it in a wide shear of the incidence and deviation angles, in a broad range of frequencies, and for both TE and TM polarizations of incident waves. The selected object of comparison is the most commonly used structure, the so-called mushroom MS, which possesses AS only for TE polarization of the incident wave and has no AS for TM-polarized waves. We show that for TE-waves a uniform mushroom MS can be used as a generic design for binary PNUMS, whereas in the TM case, the RL assumption is not valid. A comparison of these explicit examples of PNUMSs confirms our theoretical conclusions.

II. EQUIVALENCE OF RL AND AS

A. Preliminary Remarks

The deflection of plane waves by a periodic surface is described by the Floquet theory of diffraction gratings. In this theory, open diffraction channels at a given frequency are specified by the period \( D \) of the structure and the incidence angle (see [18])

\[
\sin \theta_{r,M} = -\sin \theta_i + M \lambda / D, \quad (M \in \mathbb{Z}). \tag{1}
\]

Here, \( M \) is the diffraction order number. The angles of incidence and reflection, \( \theta_i \) and \( \theta_{r,M} \), are schematically shown in Figs. 3–5. If \( M = \pm 1 \), (1) results in the relation \(|\sin \theta_{r,\pm 1} - \sin \theta_i|D = \lambda\) that we have referred above. The use of diffraction gratings allows one to engineer the amplitude of \( M \)th harmonic higher than that of the specular reflection [22], [31]. Practically, for \( M \gg 1 \), the requirement \(|\sin \theta_{r,M} - 1| < 1 \) cannot be respected if the angles \( \theta_{r,M} \) and \( \theta_i \) are not very small. For the single-user regime, one engineers the period \( D \) so that a harmonic with \(|M| = 1 \) is dominant. For the multuser regime, several harmonics with \( M = 0, \pm 1 \) or \( \pm 2 \) may be useful.

In the case of a reconfigurable MS, one period comprises a sufficient number of scattering elements that are deeply subwavelength in size. For different incidence and deflection angles, these periods can be different, but all differences between the unit cells of a PNUMS and those of the uniform MS are in the values of the loading impedances.

The RL approximation models reflection at any point \( x \) of the reflective surface by the reflection coefficient of the generic MS whose unit cells are all loaded by the same impedance \( Z(x) \). For a binary MS, the reflection phase of the generic MS whose unit cells are loaded by the impedance \( Z_0 \) (state “0”) is attributed (in this approximation) to one half-period, and the reflection phase of the generic MS whose unit cells are loaded by the impedance \( Z_1 \) (state “1”) is attributed to another half-period. First, let us prove that this approximation is not suitable for PNUMS whose generic MS has no AS.
\textbf{B. Angular Instability Disables the Approximation of RL}

Let us consider a uniform MS without AS of the reflection phase. We assume that there is a set of $N$ lumped loads $Z_1, Z_2, \ldots, Z_N$ with which the uniform MS offers different $\Phi_R$ for the normal incidence ($\theta = 0$). Let $\Phi_R^{m}(\theta_i = 0)$ corresponding to $Z_m$ ($m = 2, \ldots, N-1$) differ from $\Phi_R^{m+1}(\theta_i = 0)$ by $\pm 2\pi/N$. Then, the set $\Phi_R^{m}(\theta_i = 0)$ covers the whole range $[0, 2\pi]$. If we want to deflect the normal incident wave to the angle $\theta_i = \pi/3$ we need, in accordance to (1), the period $D = 1.16\lambda$. Postulating the RL, we engineer this period for the PNUMS taking $N$ loads and having for them $\Phi_R^{(m)}(0) - \Phi_R^{(m+1)}(0) = \pm 2\pi/N$.

No AS means that the values $\Phi_R^{m}(\theta_i)$ for a substantial incidence angle, such as $\theta_i = \pi/3$, are noticeably different from $\Phi_R^{m}(0)$. It is important to notice that the concept of AS makes sense namely for substantial incidence angle $\theta_i$ and for similarly substantial deviation angles. For small incidence angles, the majority of reflecting MSs have $\Phi_R(\theta_i) \approx \Phi_R(0)$. This is not surprising because for small angles, the period $D$ in (1) is electromagnetically large and the gradient of the local reflection phase in a PNUMS is small. We have studied several uniform reflecting MSs that potentially allow control of the reflection phase and found that for $\theta_i \ll \pi/4$ they all possess good AS. Noticeable deviations in the reflection phase from $\Phi_R(0)$ correspond to larger incidence angles.

As an example, let us consider the case when the reflection phase of the generic MS for $\theta_i = \pi/3$ is twice larger than that for the normal incidence. Then, for the same loads $Z_m$ and $Z_{m+1}$ as we used above we will have $\Phi_R^{m}(\pi/3) - \Phi_R^{m+1}(\pi/3) = \pm 4\pi/N$. In this case, postulating the RL for the PNUMS, we obtain the period equal to $D = 1.16\lambda$ for the normal incidence and $D = 0.58\lambda$ for the incidence under the angle $\theta_i = \pi/3$. A PNUMS with a so small period as $D = 0.58\lambda$ is not a phase diffraction grating, that is, for $\theta_i = \pi/3$ and $D = 0.58\lambda$ only specular reflection is possible, and there is no anomalous reflection. No power will be deflected from $\theta_i = \pi/3$ to the angle $\theta_i = 0$, though a normal incident wave nicely deflects to the angle $\theta_i = \pi/3$.

Next, let us consider the case when the reflection phase of the generic MS for $\theta_i = \pi/3$ is twice smaller than that for the normal incidence. Then, the phase difference $|\Phi_R^{m}(\pi/3) - \Phi_R^{m+1}(\pi/3)| = \pi/N$ is also twice smaller than it is in the case of the normal incidence. The same periodicity $D = 1.16\lambda$ is engineered in this case, but the reflection phase varies in the range $[0, \pi]$ instead of $[0, 2\pi]$. It means that the gradient of the reflection phase is not constant along the PNUMS and the deflection from the angle $\theta_i = \pi/3$ to the angle $\theta_i = 0$ is impossible again.

Thus, for both manifestations of angular instability—either noticeably larger or noticeably smaller values of $\Phi_R(\theta_i > \pi/4)$ compared to $\Phi_R(0)$—the transmittance from the channel $\theta = 0$ to the channel $\theta = \pi/3$ and the reciprocal transmittance from the channel $\pi/3$ to the channel $0$ turn out to be essentially different. This violation of the reciprocity theorem evidently results from the assumed RL in the absence of AS.

Similar considerations hold also for binary MSs. Assume that for $\theta_i = \pi/3$, the reflection phase significantly changes compared to $\theta_i = 0$, that is, the needed (close to $\pi$) difference can be implemented only for the normal incidence and cannot be implemented for $\theta_i = \pi/3$. Postulating RL for the binary PNUMS, that is, attributing to its half-periods the same reflection phases as those of the generic MS in the states “0” and “1,” we come to a contradiction with the reciprocity principle in the same way as for phase-gradient PNUMS. Thus, we see that the RL approximation cannot be used for a PNUMS if its generic MS does not possess AS.

\textbf{C. Relations of the AS Property With Response Locality and the Approximation of PO}

Now, let us prove the opposite statement: AS of a generic MS requires the validity of the RL approximation. In this proof, we assume that the basic requirements of RIS designs are respected: in the locally periodic approximation, the magnitude of the local reflection coefficient is equal to unity, and the reflection phase can be varied in the whole $2\pi$ range. We stress that more advanced nonlocal MS or meta-grating designs cannot, in principle, be modeled under this approximation, and we do not consider them here.

For uniform and slightly nonuniform MSs, the locality of reflection is the same as the locality of excitation of individual unit cells. This means that the excitation of each unit cell is determined only by the incident field at the position of this unit cell and its own properties, assuming that all surrounding unit cells are the same. The excitation locality, as a prerequisite for independence of array response on the propagation factor along the array, was discussed in [32]. In that paper, arrays of individual dipolar scattered were considered, and it was proved that if the near-field (reactive) interactions between unit cells are negligible, the array response does not depend on the propagation constant along the array. In [32], the array period was subwavelength, and only excitation of evanescent modes was of interest, but the results hold also for propagating harmonics, in which case the independence from the tangential propagation constant is equivalent to the AS of response. Importantly, this condition for locality of response and applicability of the approximation of RL does not mean that the unit cell interactions are negligible. The power scattered by one unit cell in free space (as a spherical wave) and the power scattered by one unit cell in a periodic array (as a contribution to plane-wave reflection) are different. However, the required smallness of reactive-field interactions ensures that the frequency response of each unit cell (its resonance frequency, etc.) does not depend on the presence and excitation of the other cells, ensuring local control of the reflection phase.

To use the results of Maslovski et al. [32] for proving the requirement of the response locality for AS, we exploit the equivalence of a generic MS depicted in Fig. 1(a) and a planar electromagnetically dense array of resonant bianisotropic scatterers sketched in Fig. 1(b). In Fig. 1(a), a generic MS illuminated by a plane wave is shown. The wave of an arbitrary polarization can be decomposed into TE and TM waves incident under the same angle $\theta$ (since there is no deflection from a uniform array with a subwavelength period, the incidence angle is denoted simply as $\theta$). The
building blocks of the planar grid are shown in blue, and the lumped loads are in green. Notice that the lumped loads in this drawing are arranged horizontally because, in the case of a vertical arrangement, they would have no impact on the reflection phase for the normal incidence. The concept of the MS implies that $kh \ll \pi$ and $ka \ll \pi$, where $h$ is the substrate thickness, $a$ is the grid period, and $k$ is the wavenumber of free space. These two inequalities form the prerequisite of MS homogenization, allowing representing it as an effective sheet of electric and/or magnetic surface currents. Conditions $\max(kla, kh) \ll \pi$ practically mean that $\max(ka, kh)$ should be smaller than unity. Assume that the reflection phase of the generic MS does not depend on the incidence angle until $\theta = \theta_{\text{max}} = \pi/3$. Specifying $\theta_{\text{max}} = \pi/3$ as an example, we have in mind our work [30]. The limit of AS is different for different generic MSs, though it makes sense only for $\theta_{\text{max}} \geq \pi/4$.

The scatterers in Fig. 1(b) are uniaxial omega particles, whose example shape is shown in the inset. The equivalence of this array to the generic MS for the case of the normal incidence was proven in [33]. It is a conditional equivalence: at different frequencies, the equivalent omega-particles may be different. However, this conditional equivalence is useful for us because the electromagnetic interactions in optically dense ($a < \lambda/2$) uniaxial bianisotropic grids were thoroughly studied in works [34], [35], [36], [37], [38], [39], [40], [41].

Let the reference particle with electric and magnetic dipole moments $p$ and $m$ be centered at the coordinate origin $A$, as shown in Fig. 1(b). If we number the particles of the array by $l$ along the $x$-axis and by $s$ along the $y$-axis, we can write

$$
\mathbf{p}_l = \mathbf{p} e^{-jk_x l a - jk_y s a}, \quad \mathbf{m}_s = \mathbf{m} e^{-jk_x l a - jk_y s a}.
$$

(2)

Here, $k_x = k \sin \theta \cos \phi$ and $k_y = k \sin \theta \sin \phi$ ($\phi$ is the angle between the incidence plane and the axis $x$). The interaction electromagnetic field (whose electric component can be denoted as $E_{\text{int}}$ and magnetic one as $H_{\text{int}}$) is the sum of the fields produced by all the particles but the reference one at $A$. Due to relations (2), $E_{\text{int}}$ and $H_{\text{int}}$ are proportional to $p$ and $m$, and we can write

$$
E_{\text{int}} = \frac{\mathbf{p}_{ee} \cdot \mathbf{p} + \mathbf{p}_{em} \cdot \mathbf{m}}{\eta}, \quad H_{\text{int}} = \frac{\mathbf{p}_{mm} \cdot \mathbf{m} + \mathbf{p}_{me} \cdot \mathbf{p}}{\eta}.
$$

(3)

where three independent dyadic parameters $\mathbf{p}_{ee}$, $\mathbf{p}_{mm}$, and $\mathbf{p}_{me}$ (the last equivalence follows from reciprocity) are called electric, magnetic, and magneto-electric interaction factors, respectively. In the general case, these values are tensors, however, the array (as well as the generic MS) is practically isotropic in the horizontal plane and its electric and magnetic polarizations have no vertical components. In this case, the interaction factors do not depend on the angle $\phi$, and each of them splits into two scalar values, one corresponding to the TM-incidence and another one to the TE-incidence [35].

The individual polarizabilities of reciprocal particles $\overline{\alpha}_{ee}$, $\overline{\alpha}_{em}$, and $\overline{\alpha}_{mm}$ (the last equivalence results from the reciprocity principle) do not depend on the presence or absence of other particles. They are defined through the local electric and magnetic fields acting on the particle

$$
\mathbf{p} = \overline{\alpha}_{ee} \cdot \mathbf{E}_{\text{loc}} + \overline{\alpha}_{em} \cdot \mathbf{H}_{\text{loc}}, \quad \mathbf{m} = \overline{\alpha}_{mm} \cdot \mathbf{H}_{\text{loc}} + \overline{\alpha}_{me} \cdot \mathbf{E}_{\text{loc}}.
$$

(4)

The individual polarizabilities in the TE and TM cases can be treated as scalar values, different for the TE and TM polarizations. Since only the tangential components of the local electromagnetic field are relevant for the array polarization, we may write for the local fields scalar relations $E_{\text{loc}} = E_{\text{ti}} + E_{\text{pr}}(\theta, \phi)$ and $H_{\text{loc}} = H_{\text{ti}} + H_{\text{pr}}(\theta, \phi)$ [35], [36]. In the TE case, the incident electric field is tangential: $E_{\text{ti}} = E_1$, whereas $H_{\text{ti}} = H_1 \cos \theta$. Vector $\mathbf{p}$ is parallel to $\mathbf{E}_1$, and vector $\mathbf{m}$ lies in the incidence plane. The TM case is dual to the TE case. After these specifications, formulas (4) can be written as scalar equations

$$
p = \alpha_{ee} E_{\text{ti}} + \alpha_{em} H_{\text{ti}}, \quad m = \alpha_{mm} H_{\text{ti}} + \alpha_{me} E_{\text{ti}}.
$$

(5)

Formulas for the reflection coefficient of an arbitrary reciprocal bianisotropic array at oblique incidence were derived in [41] [formulas (2)–(4)]. In the present case (in-plane isotropy, uniaxial omega particles), these formulas simplify and the reflection coefficients for the TE and TM cases, respectively, take the form

$$
R^{TE} = \frac{\omega}{2Ja^2} \left[ \frac{\eta \alpha_{ee}}{\cos \theta} - \frac{\alpha_{mm}}{\eta} \cos \theta + 2\alpha_{em} \right]
$$

(7)

$$
R^{TM} = \frac{\omega}{2Ja^2} \left[ \frac{\eta \alpha_{ee}}{\cos \theta} - \frac{\alpha_{mm}}{\eta} \cos \theta + 2\alpha_{em} \right]
$$

(8)

Here, $\eta = \sqrt{\mu_0/\varepsilon_0}$ is the free-space impedance. The requirement of the AS demands that

$$
\alpha_{ee}^{TE,TM} (\theta) = \alpha_{ee}^{(0)} (\cos \theta)^{\pm 1}, \quad \alpha_{mm}^{TE,TM} = \alpha_{mm}^{(0)} (\cos \theta)^{\pm 1}, \quad \alpha_{em}^{TE,TM} = \alpha_{em}^{(0)}.
$$

(9)

Here, index $(0)$ corresponds to the normal incidence. Importantly, relations (9) mean that the angle-stable arrays must be spatially dispersive, since their collective polarizabilities, unlike the reflection phase, must depend on the angle of incidence. In work [39], for any uniform lossless MS operating at the frequency of the magnetic-wall (parallel) resonance one derived the following conditions for the collective polarizabilities

$$
\eta \alpha_{ee}^{(0)} = \alpha_{mm}^{(0)} / \eta = \alpha_{me}^{(0)} \equiv \alpha.
$$

(10)

Equation (10) together with (9) ensure that reflection at any incidence angle is local. If the operational frequency is close to that of the parallel resonance but not exactly equal to it, the collective polarizabilities are complex-valued and are only
approximately balanced. For the absolute value of the balanced polarizability $\hat{\alpha}$, we obtain $|\hat{\alpha}| \approx \hat{a}^2/\omega$, whereas its phase $\Phi_{\hat{\alpha}}$ can be arbitrary. Taking into account (9) and (10), formulas (7) and (8) yield

$$\Phi_{\hat{\alpha}}^{T.E.T.M} \approx -\frac{\pi}{2} + \Phi_{\hat{\alpha}} = \text{const}(\theta).$$

Changing the unit cell load in the generic MS, that is, shifting the resonance frequency of the equivalent parallel resonant circuit of the array with respect to $\omega$, we can vary the phase of $\hat{\alpha}$ from $\Phi_{\hat{\alpha}} = -\pi$ (electric-wall reflection) to $\Phi_{\hat{\alpha}} = 0$ (magnetic wall) via $\Phi_{\hat{\alpha}} = 0$ (capacitive walls) and from the magnetic-wall reflection again to the electric wall via $\Phi_{\hat{\alpha}} > 0$ (inductive walls).

The relations between the collective and individual polarizabilities were obtained in [34] and [41]. All three interaction factors $\beta_{em,mm}$ enter the expressions $\hat{\alpha}_{T.E.T.M}^{T.E.T.M}$ derived in [34] and [41]. From [41], it is clear that the contributions of the real parts of the interaction factors into collective polarizabilities are strongly dependent on $\theta$. Yazdi and Albooyeh [41, Formula 23] can be presented sharing $\text{Re}(\beta_{em,mm}^{T.E.T.M})$ as

$$\text{Re}(\beta_{em,mm}^{T.E.T.M}) = \text{Re}(\beta_{em,mm}^{T.E.T.M})_0(\theta) + \text{Re}(\beta_{em,mm}^{T.E.T.M})_1(\theta),$$

where $\text{Re}(\beta_{em,mm}^{T.E.T.M})_0(\theta)$ and $\text{Re}(\beta_{em,mm}^{T.E.T.M})_1(\theta)$ are the real parts of the interaction factors.

The observation concludes our main proof. It only remains to show that the smallness of near-field interactions is achievable for particular MSs and is compatible with the required tunability of the reflection phase, allowing the use of RL approximation for NUNMS designs.

Systems of [41, eqs. (5) and (6)] relating the collective and individual polarizabilities are recursive, whereas explicit [34, Formulas (42)–(44)] are involved. Therefore, here we only present the result of their analysis—conditions on which the contributions of the real parts of the interaction factors dominate over the contributions of the real parts of the interaction factors.

For the normal incidence, we achieve it for any angle $\theta < \theta_{\text{max}}$. Thus, we see that the AS in the subwavelength array requires the same condition of negligible near-field interactions that are required for the applicability of the RL approximation. The collective polarizabilities of the equivalent array depend on both individual polarizabilities and interaction factors and the equivalent omega-particles must be engineered so that the contributions of the individual polarizabilities and the imaginary parts of the interaction factors dominate over the contributions of the real parts of the interaction factors.

Fig. 1. Illustration to the proof of the requirement of the response locality for AS of the reflection coefficient. (a) Generic reflecting MS is formed by an electromagnetically dense ($ka < 1$) planar grid of metal elements over a metal plane. The elements (blue) are connected to controllable lumped loads (green). (b) Equivalent MS is a planar array of uniaxial omega-particles (schematically shown in the inset). Since there is no deflection, the incidence angle is denoted simply as $\theta$. Formula (14) allows us to keep only the real parts of the interaction factors since their imaginary parts cancel out. Notice
that these imaginary parts describe the reflective properties of the array [43]. Therefore, neglecting the contributions of \( \text{Im}(\beta) \) into the reflection coefficient is possible only because these imaginary parts cancel out with the imaginary parts of the inverse polarizabilities. This is so because the left-hand sides of formulas (14) directly enter the expressions for the reflection coefficient \([34]\) and \([41]\) (see \([39], [42]\), where the normal incidence case was considered).

From formulas (13) we explicitly see that the AS demands the relative smallness only of the near-field interactions, described by the real parts of the interaction factors \([43]\). The far-field interactions expressed by their imaginary parts are never negligible. If conditions (13) are respected, for a lossless array, we obtain

$$\hat{\alpha}_{ee}^{(0)} \approx \text{Re}[\alpha_{ee}^{(0)}], \quad \hat{\alpha}_{em}^{(0)} \approx \frac{\text{Re}[\alpha_{em}^{(0)}]}{1 - jk \text{Re}[\alpha_{em}^{(0)}]/2\varepsilon_0 a^2}. \quad (15)$$

These identities express the approximation that we call excitation locality. The unit cell of our MS is excited not unlike an isolated unit cell in free space, it feels the infinite array but it feels it only through the plane wave created by it. The far-field coupling is expressed by the imaginary term in the denominator of \( \alpha_{em}^{(0)} \). The near-field interactions for the normal incidence are weak and are absent in (15) (if (13) hold). According to (12), it implies their weakness also for the oblique incidence, that is, the excitation locality remains valid in the same range of angles in which the AS holds.

Relations (15) hold for the normal incidence. For oblique incidence, the far-field coupling term in the second relation contains factor \( \cos \pm 1 \theta \). Considering the case of TE incidence and electric polarizability, we have

$$\hat{\alpha}_{ee}(\theta) \approx \frac{\text{Re}[\alpha_{ee}(\theta)]}{1 - jk \text{Re}[\alpha_{ee}(\theta)]/(2\varepsilon_0 a^2 \cos \theta)}. \quad (16)$$

We see that if one can engineer the individual (single-inclusion) polarizability \( \alpha_{ee}(\theta) \) to behave as \( \alpha_{ee}(\theta) = \alpha_{ee}^{(0)} \cos \theta \), the dependence of the collective polarizability on the incidence angle becomes \( \alpha_{ee}^{(0)} \cos \theta \), as required for the AS of the array. The same conclusion holds for the magnetic polarizability if one engineer \( \alpha_{mm}(\theta) = \alpha_{mm}^{(0)} \cos \theta \) and for the TM polarization. Thus, we see that the spatial dispersion of the array resulting in the RL can be realized by engineering the spatial dispersion of only one single array element. Now, let us discuss if this is possible for omega particles.

Actually, these angular dependencies are impossible for an omega particle made of a solid wire that is sketched in Fig. 1(b). However, this angular dependence can be approximately achieved for the polarizabilities of an omega particle made of two planar and not identical metal patches with a small gap between them \([40]\). The angular dependence \( \alpha_{mm}^{TM} \sim \cos \theta \) for this particle can be qualitatively explained very simply. The response of any reciprocal particle to the local magnetic field is in fact the response to the spatial variation of the external electric field \([43]\). For the TM case, the magnetic moment induced in the effective omega particle is maximal when the wave incidence is normal because, in this case, the electric field of the wave is polarized horizontally and both metal elements are maximally excited. Grazing incidence corresponds to a vertical electric field when the currents in the elements are not induced. The explanation of other angular dependencies is more difficult and is related to the phase relations between the currents in two planar elements that depend on the incidence angle in a different way for the TE and TM cases. These phase shifts are essentially not equal to those of the incident wave because the particle described in \([40]\) experiences electric and magnetic resonances whose bands overlap. The angular dependencies \( \hat{\alpha}_{ee}^{TE}(\theta) = \hat{\alpha}_{ee}^{(0)}(\cos \theta)^{\pm 1} \) and \( \hat{\alpha}_{mm}^{TM}(\theta) = \hat{\alpha}_{mm}^{(0)}(\cos \theta)^{\pm 1} \) can be approximately engineered using omega-particles described in \([40]\) for the angles smaller than \( \theta_{\text{max}} \approx \pi/3 \). As to the magneto-electric response of such omega-particles, it does not depend on \( \theta \) in this range of angles \([40]\).

To finalize the study of a periodic MS, let us show that the generic MS, sketched in Fig. 1(a), is really equivalent to an array of uniaxial omega particles operating in the band of their resonance. To do that we will express the collective polarizabilities of the array via the parameters of the generic MS—the sheet impedance of the grid \( \zeta_g = j \chi_g \) (it should be purely reactive for lossless grids) and the substrate thickness \( h \). In the general case, the substrate is characterized by permittivity \( \varepsilon \) that can be a tensor if the substrate is anisotropic. However, for our purposes, it is not a relevant parameter, and for simplicity of the proof, we replace the substrate material with free space.

To express the current \( \chi_m \) flowing on the metal plane and the homogenized current \( \chi_g \) flowing on the grid through the amplitude \( E_0 \) of the external electric field, we may write two boundary conditions for the tangential component \( E_t \) of the total electric field. One condition holds on the metal plane \( z = 0 \) at which \( E_t = 0 \), another one—on the grid plane \( z = h \), where \( E_t = j \chi_g J_g \). To find \( \hat{\alpha}_{ee} \) and \( \delta_{ee} \), we excite the MS by a standing wave and locate the center of the MS (plane \( z = h/2 \)) at the node of the magnetic field. To find \( \hat{\alpha}_{mm} \) (and to check that \( \hat{\alpha}_{em} = \hat{\alpha}_{me} \)), we set the node of the electric field at \( z = h/2 \). This way, we realize excitations by electric and magnetic external fields. For the two considered excitations we have, respectively

$$E_0 \cos \frac{k h}{2} - \frac{\eta J_g}{2} - \frac{\eta \chi_m e^{-jkh}}{2} = j \chi_g J_g \quad (17)$$

$$j H_0 \sin \frac{k h}{2} - \frac{J_g}{2} - \frac{\chi_m e^{-jkh}}{2} = 0,$$

$$- j H_0 \sin \frac{k h}{2} - \frac{J_g e^{-jkh}}{2} - \frac{\chi_m}{2} = 0. \quad (18)$$

In accordance with \([39]\), the collective polarizabilities of the equivalent uniaxial omega-array for the normal incidence in the case of the electric excitation are as follows:

$$\hat{\alpha}_{ee}^{(0)} = \frac{a^2 (J_g + \chi_m)}{j \omega E_0}, \quad \hat{\alpha}_{me}^{(0)} = \frac{a^2 \mu \eta h (J_g - \chi_m)}{2 E_0} \quad (19)$$

and in the case of magnetic excitation, we have

$$\hat{\alpha}_{mm}^{(0)} = \frac{a^2 \mu \eta h (J_g - \chi_m)}{2 H_0}, \quad \hat{\alpha}_{em}^{(0)} = a.$$
The condition \( \eta \hat{\alpha}_{ee}^{(0)} = \hat{\alpha}_m^{(0)} \) after substitutions of (19) into (17) and some algebra results in the system of two real-valued equations \( \cos kh + kh/2 = 1 \) and \( X_g = -\eta \sin kh/(1 + kh/2) \). The solution of this problem is presented in [39] for the case \( kh \ll 1 \). However, this solution is not relevant for us, because leaves no freedom for the reflection phase control. Instead of the exact balance of the collective polarizabilities \( \eta \hat{\alpha}_{ee}^{(0)} = \hat{\alpha}_m^{(0)} \) we will search for a condition of their approximate balance \( |\eta \hat{\alpha}_{ee}^{(0)} - \hat{\alpha}_m^{(0)}/\hat{\alpha}_m^{(0)}| \ll 1 \), which is mathematically equivalent to the requirement

\[
\left| \frac{J_g + J_m}{\eta kh} \right|^2 \ll \Re \left( \frac{J_g + J_m}{J_g - J_m} \right).
\]

In the vicinity of the parallel-circuit resonance where \( X_g = -\eta \tan kh \), we have \( |J_g + J_m| \ll \eta kh \). If \( kh < 1 \), the approximate balance condition (21) is satisfied when \( |X_g + \eta kh| \ll \eta kh \), that is, for a small detuning from the parallel resonance frequency. We see that the approximate balance of two polarizabilities \( \eta \hat{\alpha}_{ee}^{(0)} \approx \hat{\alpha}_m^{(0)} \) is compatible with arbitrary variations of the reflection phase offered by small variations of \( X_g \).

From (18) and (20), we can deduce \( \hat{\alpha}_m^{(0)} \) and see that \( \eta \hat{\alpha}_m^{(0)} \approx \hat{\alpha}_m^{(0)} \) when \( |X_g + \eta kh| \ll \eta kh \). This means that all three polarizabilities are approximately balanced in the vicinity of the parallel resonance of our MS. The absolute value of the balanced polarizability is approximately equal to \( a^2/\omega \). It is possible to show that the conditions of the excitation locality (13) can be satisfied in the whole resonance band with the properly engineered frequency dispersion of \( X_g \). For it, one may use the electric and magnetic interaction factors deduced in [43]

\[
\Re \left( \beta_{ee,m}^{(0)} \right) = \eta \frac{\cos k\rho}{k\rho - \sin k\rho} \approx \eta \frac{e^{\pm 2}}{4a^2\rho} \quad (22)
\]

where \( \rho \approx a/1.438 \).

To sum up: in this proof, we have postulated the AS of a uniform MS and have seen that it can be achieved only in case of the excitation locality expressed by relations (15), that is, when interactions of the unit cells of the array via reactive fields are negligible. The proof is valid for uniform arrays. More exactly, when the array is uniform at the wavelength scale so that the locally periodic approximation is valid. We can conclude that AS of the reflection phase is achievable when two conditions are satisfied: 1) near-field interactions between the array elements are negligible and 2) the array is uniform at the wavelength scale. We have also seen that the required spatially dispersive individual polarizabilities can be engineered by a proper choice of the top grid. It is worth noticing that the spatial dispersion on the level of an individual particle is not strong, since it does not destroy the locality of the electromagnetic response of the array. On the contrary, this weak spatial dispersion allows us to achieve RL. One can say that the spatial dispersion of a unit cell compensates for the spatial dispersion of the array.

In the above calculations, we proved that the absence of AS disables the applicability of RL for an MS with anomalous reflection. In this section, we have proven that AS demands the validity of RL for the generic MS at an arbitrary incidence angle. Additionally, we proved that the concepts of AS and RL are compatible with complete tunability of the reflection phase. For a generic MS, \( \Phi_R \) is controlled by tuning all unit cells around the parallel resonance. For a PNUMS, a spatially periodical detuning of unit cells should vary the phase \( \Phi_R(x) \) along the \( x \)-axis in accordance to the RL which should hold for such PNUMS. Thus, it appears that the AS of the generic MS and the applicability of the RL approximation to PNUMS are, in this sense, equivalent. However, it is not a strict theorem. The proof was made for a uniform array, and the above speculations about a nonuniform MS do not allow us to determine the maximal allowed deviations in the adjacent unit cells. Our analysis only shows that the AS of the generic MS requires locality of the unit-cell response in the PNUMS and that its absence leaves no chances for the validity of the RL approximation. For every explicit PNUMS, the applicability of this approximation needs to be verified.

To support our theoretical expectations, below we consider two explicit examples of PNUMSs based on two different generic MSSs: those with and without AS. Below we will see that performance estimations based on the model of local reflection coefficient (surface impedance) are successful for a PNUMS with AS (based on Jerusalem crosses) in contrast to a mushroom MS that does not possess AS.

### III. Binary MSSs with and without AS

#### A. Parameters of Generic MSSs

In paper [30], we suggested an MS with AS of the reflection phase. The suggested MS is a high-impedance surface formed by a planar grid located on top of a metal-backed dielectric layer. The grid is formed by metal Jerusalem crosses mutually connected by switchable lumped capacitors. In state “0,” the lumped capacitance is zero, while in state “1,” it is nonzero and partially shunts the capacitance of the parallel stems of two adjacent crosses. In both states “0” and “1,” the AS of the uniform MS was achieved for both TE and TM polarizations in the frequency range 4.0–5.2 GHz. Of course, the AS cannot be ideal up to the grazing incidence and for all frequencies in the targeted 20% operation band. The practical requirement for the closeness of \( \Delta \Phi_R \) to the ideal 180° was defined as the maximal allowed deviation of \( \Delta \Phi_R \) from 180° equal to 180° ± 40°. The studies of [30] have shown that the phase difference deviation is within this range for \( \theta_i < \theta_{\text{max}} \approx 60° \) for both TE and TM cases in the 20% frequency band.

In [30], we also compared this MS with the so-called “mushroom” MS, which is often used as a generic MS for microwave RISs (see [30]). We optimized a uniform mushroom MS for the same operation frequency band and two wave polarizations, but no AS was achieved for TM waves in the needed frequency band. The angle \( \theta_{\text{max}} \) for this band turns out to be small, approximately 30°. The frequency band of AS achieved for the angle \( \theta_{\text{max}} = 45° \) with the use of a high-permittivity dielectric substrate turned out to be narrow (<10%). This result agrees with some earlier works [44], [45], [46], [47]. Shabanpour and Simovski [30, Figs. 5–7], one can see the phase-frequency dispersion curves of both mushroom MS and the MS based on Jerusalem crosses calculated and measured for different incident angles.
Here, following our analytical study, our purpose is to show that the AS allows the locality of reflection for nonuniform MSs. We do it for MSs of Jerusalem crosses and for a mushroom MS illuminated by TE waves. First, we redesign a generic MS for higher frequencies, namely for 15–22 GHz. This range is chosen due to the restrictions of our experimental facilities. Scaling all geometric parameters and keeping the same permittivity of the substrate, we can redesign the MS for mm-waves. With the use of optical microlithography, manufacturing is feasible up to 100 GHz. In our experiments, we do not use electronically controllable loads of the unit cells and create a binary MS using two values of the structural capacitance in the generic MS of Jerusalem crosses. In other words, two states of the uniform MS correspond to two MSs—MS A and MS B—that differ from one another by the value of the gap \( g \) between the stems of the adjacent Jerusalem crosses and the step length \( d \).

The geometric parameters of grid A are as follows: \( a = 2.3 \text{ mm}, d = 0.5 \text{ mm}, w = 0.1 \text{ mm}, \) and \( g = 0.3 \text{ mm} \). For grid B, we have the same \( a, w \) with \( g = 0.1 \text{ mm} \) and \( d = 1.3 \text{ mm} \). Fig. 2(a) shows all these notations. The substrate is chosen as Meteorwave 8300 with the relative permittivity of \( \varepsilon_r = 3(1 - j0.0025) \) and the thickness of \( h = 0.5 \text{ mm} \). Our study (see Appendix I of [30, Appendix 1]) shows that low values of the substrate permittivity grant a wider operation band keeping the same AS (the same \( \theta_{\text{max}} \)). Therefore, we introduced an air gap of thickness \( h_1 = 1.5 \text{ mm} \) between the dielectric layer and the ground plane.

Fig. 2(b)–(d) presents the results of CST numerical simulations of the two-state reflection phase frequency dispersion for normal incidence and for \( \theta = 45^\circ \) in (c) TE-case (c) and (d) TM-case.

B. Finite Binary MSs: Diffraction Patterns

For realistic scenarios, we should numerically simulate our MS as a finite-size sample. As any anomalously reflecting MS must be nonhomogeneous over the reflecting surface, the notion of the local reflection coefficient is approximate for it. However, adequate approximations are sufficiently accurate. To minimize the nonhomogeneity effects and enable adequate testing of the RL concept for our binary MS, we select as an object for comparison an array of alternating PEC and PMC strips. As PEC and PMC reflectors are perfectly local, the only internal nonhomogeneity of such idealized binary MS is a set of junctions between the strips. The parasitic effect of these junctions evidently decreases versus the strip width. Recall that to achieve the anomalous reflection this width must exceed \( \lambda/2 \). Is it enough to neglect the parasitic effect of the junctions? The comparison with full-wave simulations reported below answers this question.

Indeed, the induced surface currents are perturbed also by the edges of the MS, which results in a coupling of evanescent
harmonics and propagating ones, affecting the sidelobe pattern. With this in mind, we still expect to confirm that the AS of an infinite homogeneous MS will allow us to obtain an accurate prediction based on the RL concept for a finite binary MS. The validation by full-wave simulations is expected for both the idealized MS of PEC/PMS strips and our MS based on Jerusalem crosses.

The total size of the finite binary MSs in numerical simulations was selected as 92 × 92 mm², corresponding to 40 × 40 unit cells. Depending on the needed deflection angle one-half period $L(D/2, D/2)$ can comprise from 5 × 5 to 10 × 10 identically loaded unit cells. One half-period is identified with the state “0” (MS A) or “1” (MS B) previously engineered for a uniform and infinite MS. The case when half-periods include five unit cells corresponds to $D = 1.3\lambda_0$, where $\lambda_0$ is the free-space wavelength at 17 GHz.

Upon illuminating by an obliquely incident plane wave with $\theta_i = 15^\circ$ (TE case in Fig. 3(a)–(d)), the main diffraction lobes are oriented along two reflection angles $\theta_r = 30^\circ$ in the first case and $\theta_r = 15^\circ$ in the second case. For better visibility, we assign a sign minus to the angles corresponding to the half-space of specular reflection. The scattering directions exactly coincide with the predictions of the theoretical model. In this example, the Floquet spectrum of the MS has two propagating harmonics, corresponding to $M = 0, +1$. Besides these two propagating modes, the rest of the spatial spectrum, including $M = -1$ is evanescent. As depicted in Fig. 3, the power radiated to side lobes is very small. The existence of these lobes is related not only to an error of the RL approximation of the infinite binary MS but to the finite size of the simulated one.

As depicted in Fig. 3(a)–(d), in the two reciprocal situations, we have $\theta_{r,0} = -15^\circ$ or $\theta_{r,0} = -30^\circ$ as the specular reflection angle. In both cases, the specular reflection is noticeably lower than the deflection in the desired directions. For the quantitative analysis, we also plot in Fig. 3, the bistatic radar cross sections of our MS versus the scattering angle $\theta$ in the $xoz$ plane together with the corresponding 3-D far-field scattering patterns. From Fig. 3(a)–(d), we see that the polarization stability of our MS is respected with excellent accuracy.

In the following numerical example, we conduct a comparison between a binary angle-stable MS and a binary mushroom MS (angle-dependent MS) with identical overall sizes and periods. The main goal is to compare the full-wave simulations of the actual structures with simple analytical models based on the local input impedance approximation. As a reference structure, we use a binary reflector formed by PEC and PMC strips, because in this case we have the same $\pi$ difference of the local reflection phases and these reflection phases do not depend on the incident angle.

Fig. 4 shows the scattering pattern for the TE polarization, where the incident angle is set to $\theta_i = 15^\circ$. The 2-D bistatic RCS pattern depicted in Fig. 4(a) and (b) demonstrates that the scattering pattern of the PEC/PMC binary MS closely resembles that of the angle-stable MS. Particularly, the maximum in the anomalous reflection toward the first diffraction order (the desired direction) coincides with the corresponding maximum for the PEC/PMC binary MS. However, the results for the mushroom structure [Fig. 4(b)] as an angle-dependent MS exhibit a significant deviation from the RL approximation. In this scenario, the specular reflection (undesired direction) is even greater than the anomalous reflection toward $\theta_{r,1} = -30^\circ$. Thus, this example clearly illustrates that the scattering pattern of the angle-stable MS adheres to the approximation of RL, thereby validating our analytical proof.

It is important to note that, to ensure a fair comparison with the PEC/PMC binary MS, the reflection phase difference (in
Fig. 4. Comparison of 2-D diffraction patterns plotted versus $\theta$ in the $XOZ$ plane (TE polarization at 17 GHz) for (a) angle-stable and (b) angle-dependent MS with the same sized PEC/PMC binary MS. (c) 3-D scattering pattern for the three binary MSs with the same dimensions under the same illumination angle $\theta_i = 15^\circ$. In the insets, one period and a half-period of each MS are shown.

Fig. 5. Comparison of 2-D diffraction patterns plotted versus $\theta$ in the $xoz$ plane (TE polarization at 17 GHz) for (a) angle-stable and (b) angle-dependent MS with the same sized PEC/PMC binary MS. (c) 3-D scattering pattern for the three proposed same sized binary MS under the same illumination angle $\theta_i = 30^\circ$. The comparison yields an exceptionally good agreement, particularly evident in the maxima of the anomalous reflection toward the desired direction ($\theta_r + 1 = 15^\circ$). These examples provide compelling evidence that verifies the analytical proof we have put forth regarding the equivalence of AS and RL. For completeness, we present the corresponding pattern also for the mushroom layer MS in Fig. 5(b). Significant differences between the two curves are manifestations of the angular dependence of the mushroom MS response.

the two states of the corresponding generic MS) of both the angle-stable and angle-dependent MS should be 180$^\circ$. This is precisely why we selected a small incident angle of $\theta_i = 15^\circ$ in the previous example. At this small incident angle, both the mushroom MS and the angle-stable MS exhibit the desired 180$^\circ$ phase difference in their generic MS for states “0” and “1.”

For larger incident angles, the mushroom MS fails to meet the aforementioned criteria due to the angular dependency of its response, while the angle-stable MS maintains the required phase difference between the “0” and “1” states of the binary MS up to $\theta_i = 30^\circ$. Fig. 5(a) provides a comprehensive comparison between the scattering patterns of the designed angle-stable MS and the PEC/PMC binary MS for the incident angle of $\theta_i = 30^\circ$. The comparison yields an exceptionally good agreement, particularly evident in the maxima of the anomalous reflection toward the desired direction ($\theta_r + 1 = 15^\circ$). These examples provide compelling evidence that verifies the analytical proof we have put forth regarding the equivalence of AS and RL. For completeness, we present the corresponding pattern also for the mushroom layer MS in Fig. 5(b). Significant differences between the two curves are manifestations of the angular dependence of the mushroom MS response.
Fig. 6. (a) Schematic 3-D view of the measurement setup. The remote-controlled rotating platform with (b) metal plate and (c) designed MS.

Fig. 7. Measured normalized refracted intensity color maps for TE-polarized incident wave at (a) 16 GHz, (b) 17 GHz, and (c) 18 GHz. (d)–(f) Same results for the TM-polarized incident wave. The dotted green lines show the analytical predictions. White areas show blind spots.

Fig. 8. Comparison of 2-D scattering patterns plotted versus $\theta$ in the $xz$ plane between the experimental and numerical results under illumination of TE-polarized wave with (a) $\theta_i = 0^\circ$ and (b) $\theta_i = 62^\circ$.

IV. EXPERIMENT

In this section, we present the experimental results validating the theoretically predicted scattering pattern for the binary PNUMS engineered, simulated, and discussed above. We have measured the diffraction pattern in the symmetrically located vertical plane at the Ku/K band (15–22 GHz) and compared it with the predictions of the model. Each half-period formed either by MS A or MS B contains $5 \times 5$ unit cells (10 unit cells per period $D$). To measure the diffraction pattern for varying incidence angles, we used the NRL Arc setup [48]. In this setup, two linearly polarized horn antennas covering the frequency range of 15–22 GHz were used as Tx and Rx ones. As depicted in the 3-D model view [see
effects between the antennas and reflections from the setup close to the far-field region. To exclude the mutual coupling equal to 50 cm, which corresponds to the intermediate zone, the distance between the MS and the transmitting antenna was 62 cm. In this work, we studied the relation between the AS of a generic MS used for the design of a RIS and the applicability of the approximation of RL to its nonuniform counterpart—nonuniform periodical MS. Majority of researchers utilize this approximation in the context of the generalized reflection law, not considering its applicability limits. This can result in serious errors that arise when the incidence or deviation angles are large. However, there are MSs to which the RL approximation is applicable even for large angles. Only in these cases do the unit cells of a nonuniform MS behave as the unit cells of MSs designed using the local periodical approximation.

The main message of this article is twofold: 1) the approximation of RL commonly adopted by specialists developing RISs may be not applicable for large incidence and deviation angles and 2) however, if the corresponding generic (uniform) RIS has AS of the reflection phase, the RL approximation applies to nonuniform RISs, even if this RIS is strongly nonuniform, for example, binary. These messages are supported by analytical studies, numerical examples, and an experiment. We have demonstrated the predicted operation of the binary MS that offers RL up to the incidence and deviation angles $-75^\circ < \theta < 75^\circ$ in the 20% frequency band for both polarizations of the incident wave. We believe that this MS (based on Jerusalem crosses) is promising for binary RISs. To achieve tunability, the loading capacitances that were fixed in the present study should be replaced either by electronically biased pin diodes or by optically biased photosensitive elements such as metal–insulator diodes.

To make the main message of the article more convincing, we numerically studied the so-called mushroom MS, which we optimized for the same frequency band and both polarizations. We observed that the diffraction pattern has significant deviations from the predictions of the RL-based model. No doubt, this is so because the reflection phase of the mushroom MS in the case of TM polarization is not angularly stable. For TE-polarized waves, the mushroom MS is angularly stable and the results of full-wave simulations qualitatively fit the model.

V. CONCLUSION

In this work, we studied the relation between the AS of a generic MS used for the design of a RIS and the applicability of the approximation of RL to its nonuniform periodical MS. Majority of researchers utilize this approximation in the context of the generalized reflection law, not considering its applicability limits. This can result in serious errors that arise when the incidence or deviation angles are large. However, there are MSs to which the RL approximation is applicable even for large angles. Only in these cases do the unit cells of a nonuniform MS behave

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