论文推荐 ｜ 复杂介质中无线通信的波前整形：从时间反演（TR）到可重构智能表面(RIS)

临菲信息技术港

推荐原文及其相关

G. Lerosey and M. Fink, "Wavefront Shaping for Wireless Communications in Complex Media: From Time Reversal to Reconfigurable Intelligent Surfaces," in Proceedings of the IEEE, 2022
（可在临菲网站首页下载原文）

本文作者之一 Mathias Fink 是时间反演信号处理领域的**领军人物**

写在前面

TR：time reversal，时间反转，时间反演

TRM：TR mirror，时间反演镜（采用时间反演的原理使波聚焦的装置）

RIS：reconfigurable intelligent surface，可重构智能表面

正文

摘要：可重构智能表面（RISs）在无线通信领域获得了巨大的发展动力，因为它们带来了范式的转变。事实上，它们可以使任何环境具有电磁智能和动态可重构性，以实现更高效和更环保的无线通信。作为物理学家，我们几乎在十年前就提议使用电子可调谐的元表面来塑造承载反射性的无线通信的电磁波，这是受我们和同事在复杂介质中的波控制领域的一些工作的启发。在这篇文章中，我们从最初的时间反演开始，回顾了我们提出这一概念的开创性工作。然后，我们通过与相位共轭的比较来提出物理学家对 RIS 的看法。最后，这既依赖于我们对波控的了解，也依赖于我们对它们十年来的研究，我们强调了它们的局限性。

关键字：5G 移动通信；6G 移动通信；元表面；可重构智能表面（RIS）

I. 引言

II. 从时间反演到 RIS

A. 时间反演方法

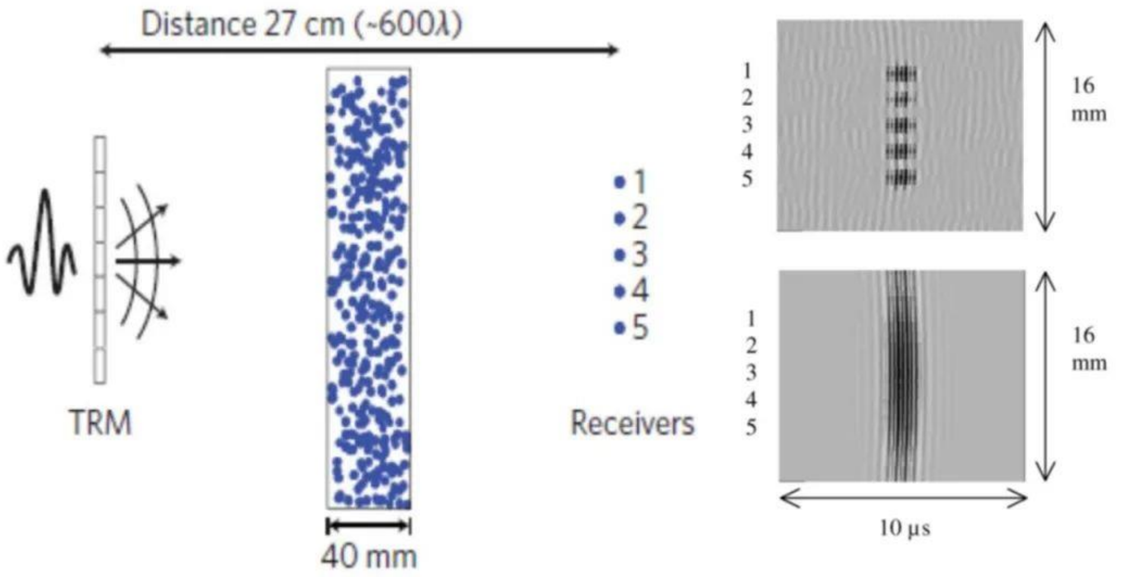

Fig. 1. *(From [23]) Left: ultrasonic TR focusing is used to focus wave spatiotemporally onto five different foci from an array of 23 antennas. Right top: result obtained in the presence of a multiply scattering medium. As the scattering medium acts as a focusing lens of great angular aperture, each individual focal spot is much thinner, and five independent beams are created allowing spatial multiplexing with independent and closely spaced focal spots. Right down: result obtained in free space. The beam is much larger, and there is no more spatial multiplexing possible in this configuration.*

<u>左图</u>：超声 TR 聚焦用于将波从 23 个天线阵列的时空上聚焦到五个不同的焦点。

<u>右上图</u>：在有多重散射介质的情况下得到的结果。由于散射介质充当了大角度孔径的聚焦透镜，每个单独的焦点要细得多，并产生了五个独立的波束，允许用独立和紧密间隔的焦点进行空间复用。

<u>右下图</u>：在自由空间获得的结果。波束要大得多，在这种配置下不可能有更多的空间复用。

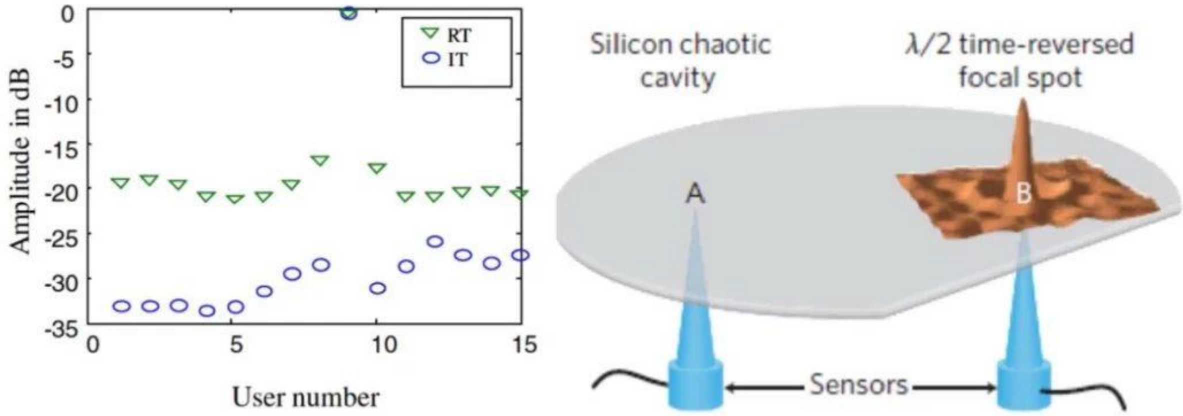

Fig. 2. *(From [27]) Left: spatial multiplexing on 15 receivers. Instead of using the classical TR approach to create 15 different beams, iterative TR converges to a regularized inverse filter, allowing spatial focusing with much lower sidelobes than TR, at the price of lower efficiency. The figure shows the maximum level of the interference noise on the other users when a pulse is focused on one user (number 9). The iterative method (IT) reduces the interference by nearly 13 dB compared to standard TR. (From [28]) Right: in an ultrasonic chaotic cavity, a single source at A emits the time-reversed impulse response from B to A, hence leading to a half-wavelength wide measured focal spot around B.*

<u>左图</u>：15 个接收机上的空间多路复用。在不使用经典的 TR 方法的情况下创建 15 个不同的波束，而是用迭代 TR 收敛到一个正则化的反向滤波器，允许以比 TR 低得多的旁瓣进行空间聚焦，代价是效率较低。图中显示了当一个脉冲集中在一个用户（9 号用户）上时，其他用户的干扰噪声的最大水平。与标准 TR 相比，迭代法减少了近 13 分贝的干扰。

<u>右图</u>：在无声混沌腔中，A 处的单一声源从 B 处向 A 处发射时间反演的脉冲响应，因此导致 B 处周围出现半波长宽的测量焦点。

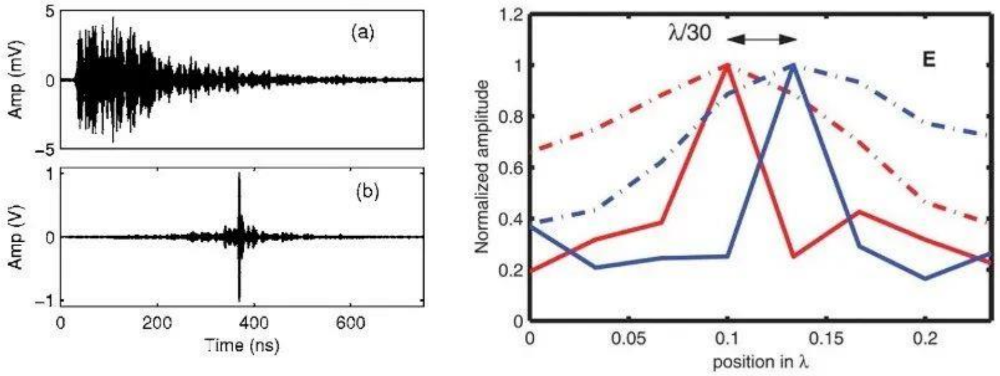

Fig. 3. ***(From [35]) Left: first experimental demonstration of electromagnetic TR in a microwave cavity, showing the achieved temporal compression. (From [37]) Right: if the receiving antenna is placed in a medium made out of subwavelength spaced resonant scatterers, focal spots much thinner than half-wavelength can even be obtained.***

左图：在微波腔中首次实验证明了电磁 TR，显示了实现的时间压缩。

右图：如果接收天线放置在由子波长间隔的谐振散射体组成的介质中，可以获得比半波长还要细的焦点。

B. 利用空间光调制器进行光波前整形

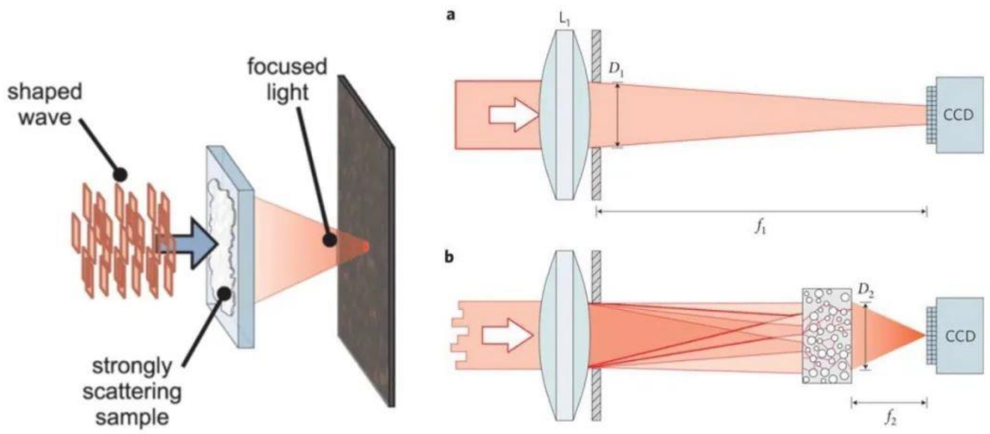

Fig. 4. ***(From [40]) Left: wavefront shaping: using arrays of pixels that control the phase of the light that they reflect, so-called SLMs; it is possible to concentrate light on a wavelength-sized focus after propagation through a thick layer of paint. (From [33]) Right: similar to TR through complex scattering media, wavefront shaping through a layer of strongly scattering material can increase the aperture of a lens, resulting in a much thinner focal spot.***

左图：波前整形：使用像素阵列来控制它们所反射的光的相位，即所谓的 SLMs；在通过厚厚的油漆层传播之后，有可能将光集中在一个波长大小的焦点上。

右图：与通过复杂散射介质的 TR 类似，通过一层强散射材料的波前整形可以增加透镜的孔径，从而产生一个更细的焦距点。

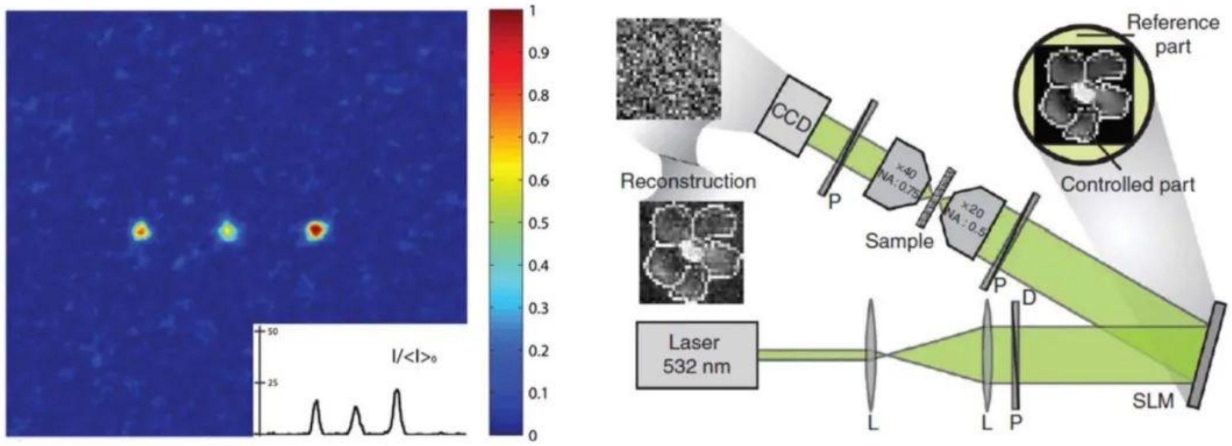

Fig. 5. ***(From [45]) Left: using the knowledge of the transmission matrix between 60 000 points on an SLM and a CCD; Popoff et al. [45] showed that they could focus light on multiple points through multiple scattering media, similar to massive-MIMO-Mu. (From [46]) Right: knowledge of such a matrix even allows to transmit an image with high fidelity through a very scattering medium.***

左图：利用 SLM 和 CCD 上 60000 个点之间的传输矩阵的了解，Popoff 等人表明，他们可以通过多个散射介质将光聚焦在多个点上，类似于大规模 MIMO-Mu。

右图：对这样一个矩阵的了解甚至可以通过一个散射能力强的介质来传输一个高保真的图像。

C. 空间微波调制器（SMM）：反射式 RIS 的祖先

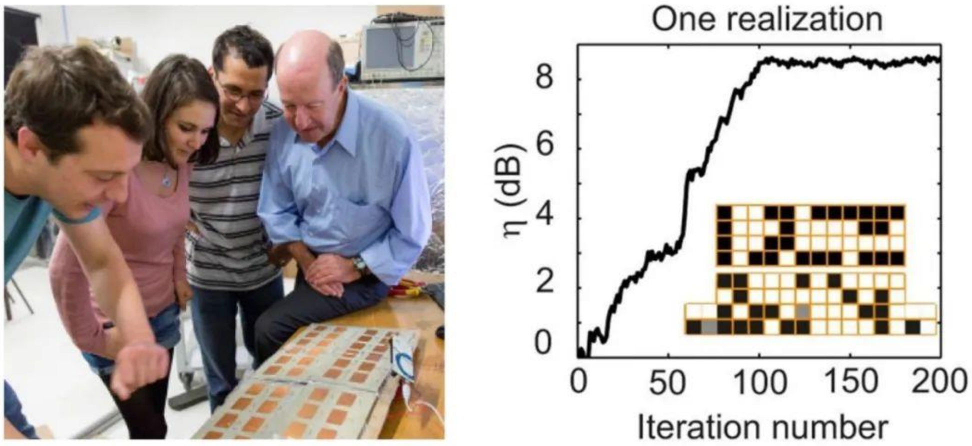

Fig. 6. *Right: photograph from French newspaper “Le Monde” in 2014, showing the first RIS developed at the Institut Langevin for operation at 2.45 GHz to exemplify an article titled “A smart wall that dresses electromagnetic waves.” (From [18]) Right: in a typical office, the electronically tunable metasurface used as a RIS allowed on average a tenfold improvement of the energy received on an isotropic antenna.*

左图：法国报纸 《世界报》2014 年的照片，显示了朗文研究所开发的第一个在 2.45GHz 下工作的 RIS，以例证一篇题为”A smart wall that dresses electromagnetic waves ”的文章。

右图：在一个典型的办公室里，作为 RIS 使用的电子可调谐元表面使同位素天线接收的能量平均提高了 10 倍。

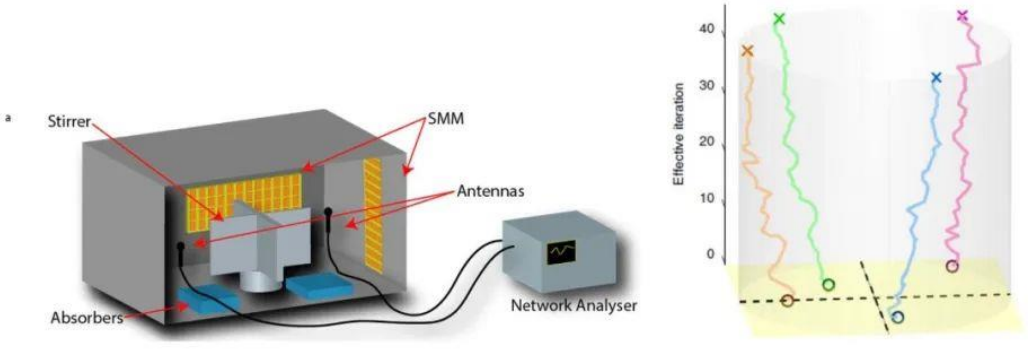

Fig. 7. *(From [47]) Left: using tunable metasurfaces or RIS as the walls of a cavity, one can design electromagnetically reconfigurable cavities with on-demand eigenmodes, for antenna applications, for instance. (From [48]) Right: RIS can also be used alongside MIMO systems to shape the communication channel and, therefore, enhance the Shannon capacity.*

左图：使用可调谐的元表面或 RIS 作为腔体的壁，即可以设计出具有按需特征模式的电磁可重构腔体，用于天线的应用。

右图：RIS 也可以与 MIMO 系统一起使用，以塑造通信通道，从而提高香农容量。

III. 从时间反演到 RIS：一个物理学家的观点

A. 作为匹配滤波器的相位共轭镜

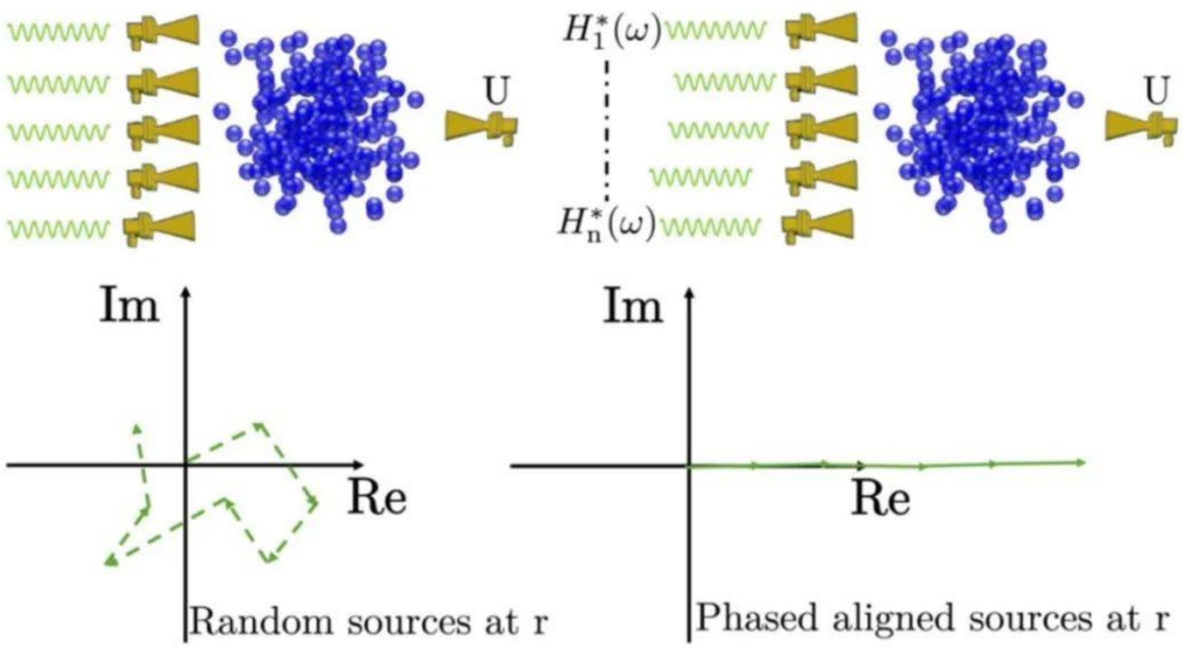

Fig. 8. *Left: when a set of n monochromatic sources sends waves in synchrony through a complex medium, the wave field at a given location can be seen as a sum of random phasors, and the resulting signal picked at this location if a random walk on the complex plane of extension n in energy. Right: using phase conjugation, the knowledge of the transmission matrix between each source and the target point allows synchronizing all the phasors coming from the various sources, resulting in energy at the focal point proportional to n^2.*

左图：当一组 n 个单色源在复杂介质中同步发送波时，在某一特定位置的波场可以被看作是随机相位的总和，那么在这一位置挑选的结果信号出现在能量扩展为 n 的复平面上随机移动

右图：利用相位共轭，了解每个源和目标点之间的传输矩阵，可以使来自不同源的所有相位同步，从而使焦点处的能量与 n^2 成比例。

B. 作为两相共轭镜的产物的 SISO-RIS

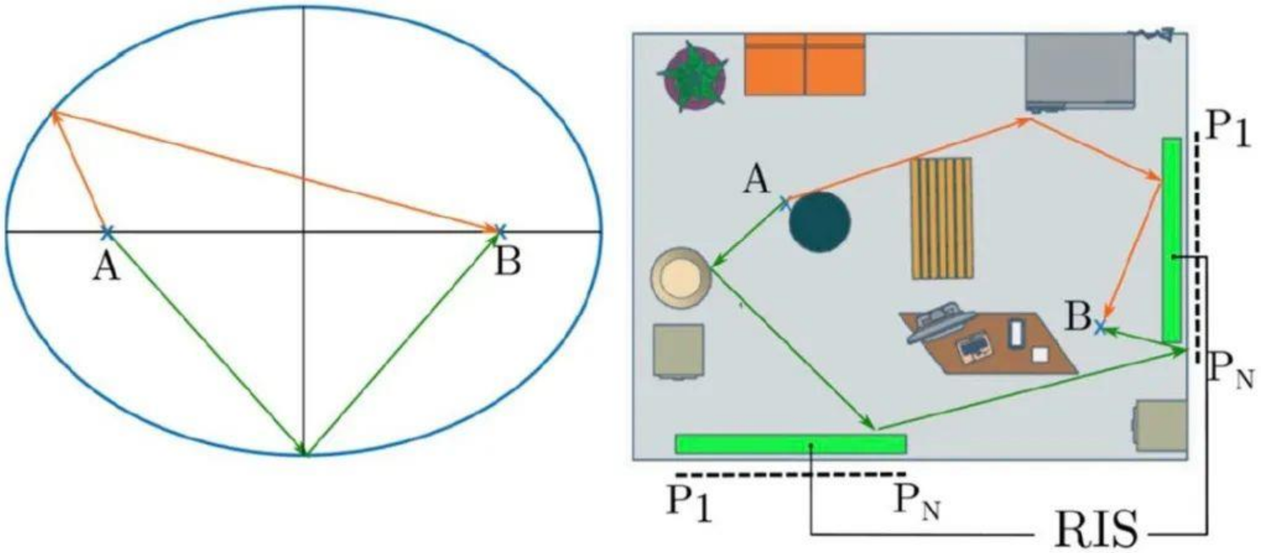

Fig. 9. *Left: very illustrative way of thinking about RIS is to consider waves propagating in an ellipse: if the emitter A and the receiver B or both placed at the foci of the ellipse, then any wave coming from A reaches B in synchrony, and vice versa, resulting in maximum energy transmission. Right: idea of using RIS in an environment is to make sure that most waves that come from A and propagate in the medium reach B, thanks to smart control of the waves' reflections by the RIS.*

左图：思考 RIS 的非常直观的方式是考虑波在椭圆中的传播：如果发射器 A 和接收器 B 都放在椭圆的焦点上，那么来自 A 的任何波都会同步到达 B，反之亦然，导致最大的能量传输。

右图：在该环境中使用 RIS 的想法是通过 RIS 对波的反射的智能控制确保大多数来自 A 的波在介质中传播时到达 B。

C. 二进制相位调制镜

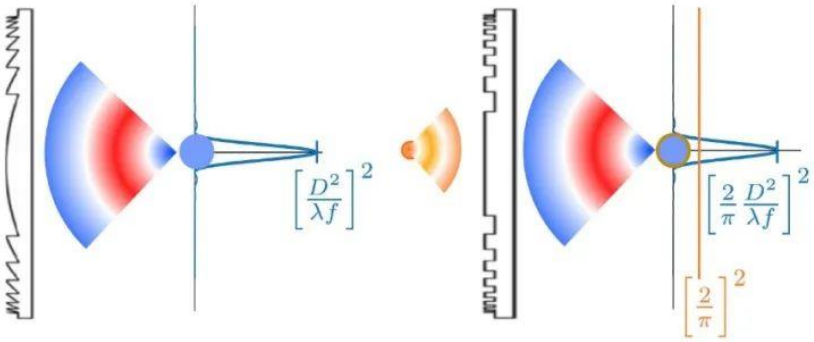

Fig. 10. *Left: similar to a lens, an RIS with a continuous phase control profile can focus waves at a distance with a resolution imposed by its typical size and the focal distance, giving a compression gain in energy. Right: difference between the previous continuous phase RIS and a binary discretized one is that, while the binary one also converges to a focal spot (of slightly lower energy), it also gives rise to background sidelobes that are due to a diverging wave, the effect of which becomes negligible compared to the main lobe as the RIS size increases.*

<u>左图</u>：与透镜类似，具有连续相位控制曲线的 RIS 可以在一定距离内聚焦波，其分辨率由其典型尺寸和焦距决定，从而在能量上有一个压缩增益。

<u>右图</u>：连续相位 RIS 和二进制离散 RIS 的区别在于，虽然二进制 RIS 也会收敛到一个焦点（能量略低），但它也会产生背景旁瓣，这是由于发散的波，随着 RIS 尺寸的增加，其影响与主瓣相比变得可以忽略不计。

D. 混响和多重散射介质中的 RIS

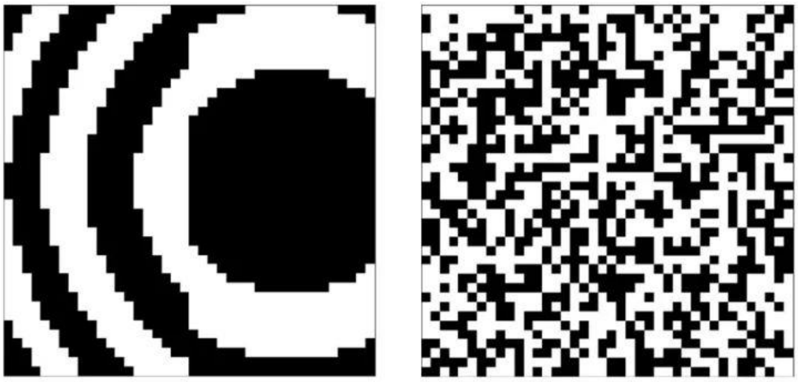

Fig. 11. *Left: typical control pattern imposed to an RIS in order to realize beamforming to a couple of far-field located points (white diode reverse and black diode forward). Fresnel zones are clearly visible. Right: control pattern imposed to an RIS after optimization in a complex scattering medium. This pattern is much more random, and Fresnel zones have been replaced by a low correlation length random pattern. This translates to identical energy deposited at the focus but lower sidelobes due to the binary nature of the RIS.*

<u>左图</u>：强加给 RIS 的典型控制模式，以实现对几个远场点的波束成形（白色二极管反向和黑色二极管正向）。菲涅尔区清晰可见。

<u>右图</u>：在复杂的散射介质中，优化后的控制图施加在 RIS 上。这个图更加随机，菲涅尔区已被低相关长度的随机模式所取代。这意味着在焦点处沉积了相同的能量，但由于 RIS 的二元性质，旁瓣较低。

E. 与自由空间全息技术的联系

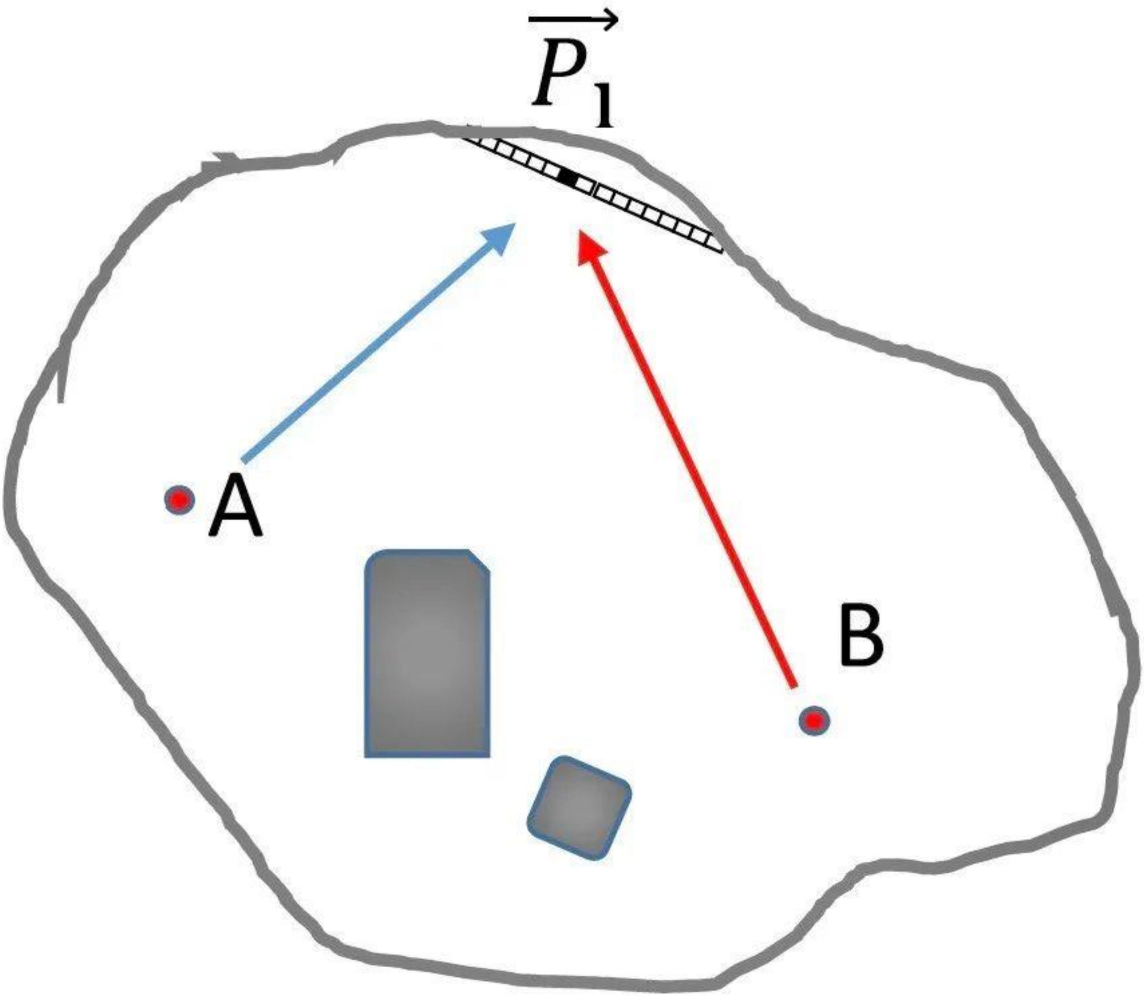

Fig. 12. *Holographic point of view. The two waves originating from antenna A and antenna B interfere on the RIS plane where the coordinates of each pixel is $\vec{P}_i$. The measured intensity pattern is, therefore, the one given by formula (9).*

全息的角度。来自天线 A 和天线 B 的两个波在 RIS 平面上发生干涉，其中每个像素的坐标为 $\vec{P}_i$。因此，测量的强度是由公式（9）给出的。

F. 归纳为 MISO 或 MIMO RIS

IV. 从时间反演到 RIS：一个先驱者的观点

A. 6GHz 以下频段的 RIS:自主性是必须具备的

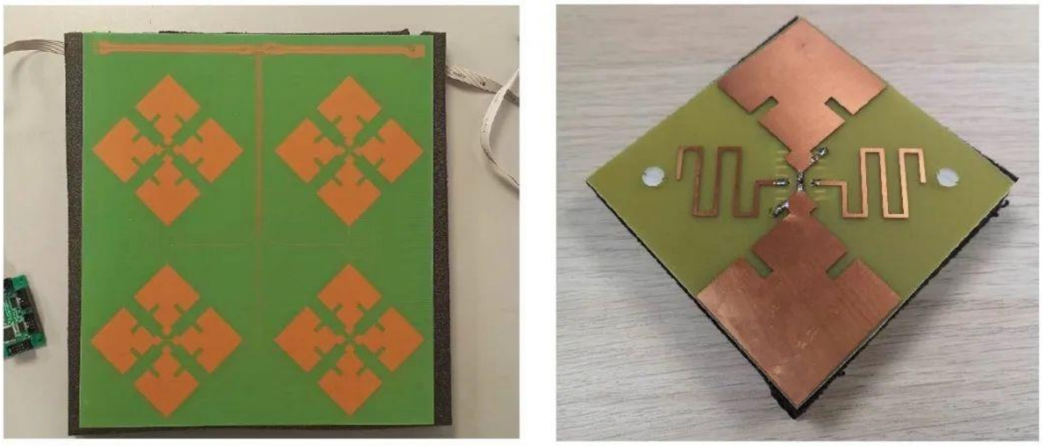

Fig. 13. *Left: conventional tunable metasurfaces, or RIS, are matrices of multiple identical pixels that contain electronic tuning components, such as p-i-n diode or varactors. These RISs are connected to a central board that is used to both power and control independently each tuning element. Here, an example at the frequency of RFID. Right: energy autonomous and wirelessly controlled RIS unit cell has been developed in the context of RFID. The horizontal polarization is used to harvest energy from the RFID waves using an RFID powered and controlled chip from EM microelectronic. The latter uses RFID commands to forward or reverse bias a p-i-n diode used to modify the phase response of the vertical polarization. This unit cell, which can shape electromagnetic waves of vertical polarization, is, hence, wirelessly controlled and powered with a use range larger than 10 m.*

<u>左图</u>：传统的可调谐元面，或称 RIS，是由多个相同的像素组成的矩阵，包含电子调谐元件，如 p-i-n 二极管或变阻器。这些 RIS 连接到中央板上，用于独立地给每个调谐元件供电和控制。这是 RFID 频率下的一个例子。

<u>右图</u>：在 RFID 的背景下，已经开发了能量自主和无线控制的 RIS 单元电池。水平极化被用来从 RFID 波中收集能量，使用 EM 微电子的 RFID 供电和控制芯片。后者使用 RFID 指令对一个 p-i-n 二极管进行正向或反向偏压，用于修改垂直极化的相位响应。这个可以塑造垂直偏振电磁波的单元格，因此是无线控制和供电的，使用范围大于 10 米。

B. 毫米波 RIS：无源接入点扩展器

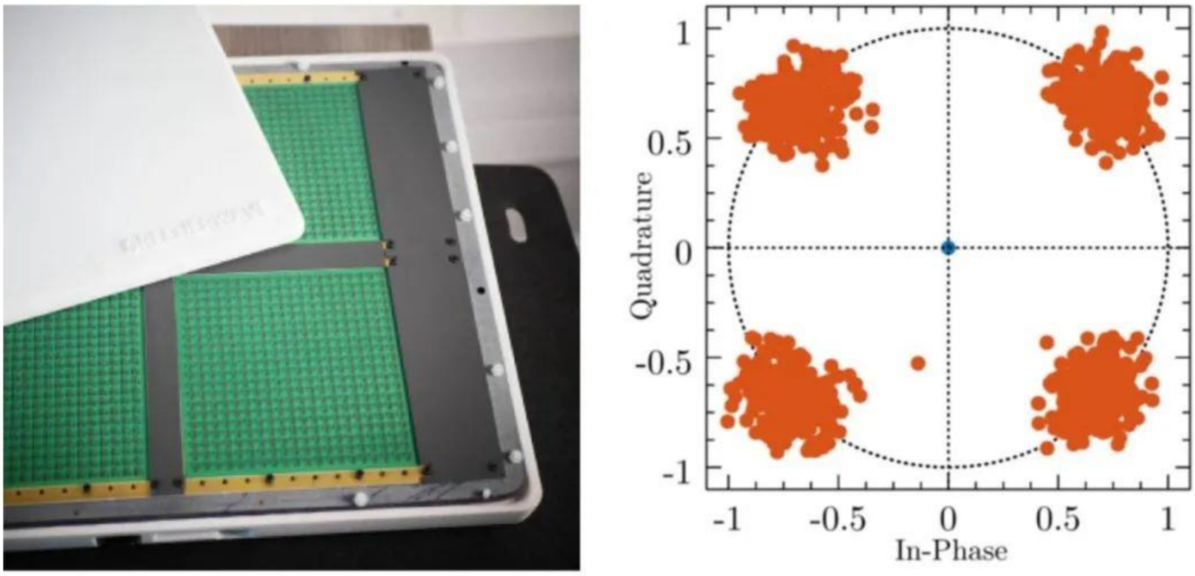

Fig. 14. ***(From [65]) Left: 20 cm * 20 cm, 40*40 dual-polarized unit cell RIS containing 3200 p-i-n diodes is used as a passive mmWave access point extender at 28 GHz. (From [65]) Right: IQ diagram of the signal received, for Rx and Tx antennas in nonline-of-sight configuration and at 10 m when an RIS placed between them is not optimized (blue dots very close to origin) and when it is optimized (red dots). The use of the RIS brings a gain larger than 25 dB and allows perfect decoding of the information, while it is completely lost without it.***

左图：20 厘米 x20 厘米，包含 3200 个 p-i-n 二极管的 40x40 双极化单元单元 RIS 被用作无源毫米波。接入点扩展器，频率为 28GHz。

右图：接收信号的 IQ 图，Rx 和 Tx 天线在非视线配置和 10 米处，当 RIS 放置在它们之间未被优化时（非常接近原点的蓝点）和被优化时（红点）。RIS 的使用带来了大于 25dB 的增益，并允许完美的信息解码，但没有它则会完全失去信息。

C. 常见问题：实际应用中的 RIS 优化

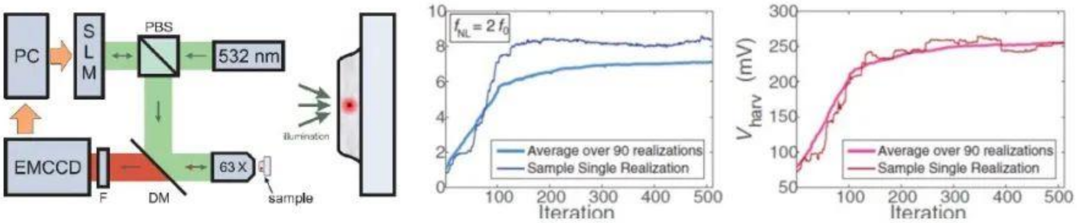

Fig. 15. *(From [66]) Left: experimental setup used in optics to focus green light deep inside strongly scattering media using red light scattered by a fluorescent probe. (From [67]) Right: equivalent experiment in the context of wave field control using tunable metasurfaces; RIS is used in a cavity to focus 2.45-GHz waves onto an energy harvesting circuit using a rectifier. The optimization of the RIS is realized using the second harmonic generated in the cavity by the rectifier (blue curve), while the voltage harvested is monitored and demonstrated actual focusing of 2.45-GHz waves using the generated harmonic spurious (red curve).*

左图：光学中使用的实验装置，利用荧光探针散射的红光在强散射介质的深处聚焦绿光。

右图：在使用可调谐元表面进行波场控制的背景下进行的等效实验；RIS 被用于一个腔体中，将 2.45-GHZ 的波聚焦到使用整流器的能量采集电路上。RIS 的优化是使用整流器在腔中产生的二次谐波（蓝色曲线）实现的，同时使用产生的谐波杂散（红色曲线）监控并展示 2.45-GHz 波的实际聚焦。

V. 总结

（略）