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Wavefront Shaping for Wireless Communications in Complex Media: From Time Reversal to Reconfigurable Intelligent Surfaces

This article provides an overview of the research works and enabling technologies that have underpinned the development of reconfigurable intelligent surfaces.

By Geoffroy Lerosey and Mathias Fink

ABSTRACT | Reconfigurable intelligent surfaces (RISs) are gaining huge momentum in the field of wireless communications due to the paradigm shift that they bring. Indeed, they allow making any environment electromagnetically smart and dynamically reconfigurable for more efficient and greener wireless communications. As physicists, we proposed to use electronically tunable metasurfaces to shape the electromagnetic waves carrying our wireless communications in reflection almost ten years ago, inspired by some works that we and colleagues did in the field of wave control in complex media. In this article, we review the seminal works that led us to propose this concept, starting from the original one that is time reversal. Then, we propose a physicist's point of view of RISs using a comparison with phase conjugation. Finally, we highlight what we think are their limitations, relying on both our knowledge of wave control and our study of them over a decade.

KEYWORDS | 5G mobile communication; 6G mobile communication; metasurfaces; reconfigurable intelligent surfaces (RISs).

I. INTRODUCTION

Due to the ever-increasing demand for wireless data transmission over the past decades, engineers and researchers in various communities, from electrical engineering to mathematics, have been working hard to find new means to improve their quality of service, data rate, and global coverage. From the Global System for Mobile Communication (GSM), the first generation of cellular communications, to the current deployment of 5G, amazing new technologies have been introduced to do so. These great innovations have concerned all the chains of a wireless system [1]–[7].

1) Error-correcting codes have been introduced to secure the integrity of data decoding.
2) Code-division multiple access or orthogonal frequency-division multiplexing has been implemented to counter the detrimental effects of wave propagation in complex urban or rural environments.
3) Multiple-input/multiple-output systems have been proposed to harness multipathing for increased channel capacity and ultimately deliver higher data rates to users.

In parallel, there have been tremendous efforts devoted to the understanding of wave propagation in complex media from a fundamental point of view in the physics community. This started originally in optics with the study of multiple scattering of waves and intriguing effects, such as coherent backscattering, and quickly reached other fields where wave control in complex media for imaging,

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communication, or energy deposition purposes started to gain momentum. Particularly, ultrasonic waves proved to be very effective for that matter since the domain benefited very early, with the advances in ultrasonography, agile arrays of transducers and *ad hoc* hardware for data acquisition and generation. In particular, time reversal (TR), an approach based on the time symmetry of the wave equation and relying on arrays of time-controlled active sources, was proposed early in the 1990s by Fink [8], [9]. Several researchers belonging to his Paris group demonstrated it to be a very efficient means to focus ultrasonic waves onto very sharp focal spots, especially in very complex, scattering, or reverberating environments. These ideas quickly reached other fields of wave physics and, in particular, optics. In this domain, researchers were limited by the equipment at their disposal, and hence, they started to control light propagation in complex media using tunable mirrors made of matrices of pixels whose reflectance can be modified, instead of programmable sources. This is how was introduced the idea of wavefront shaping in optics.

These works in optics were extremely inspiring for us, as they showed that, instead of controlling many sources for efficient beamforming, it is sufficient to control the reflections of a single source off several tunable reflectors used as Huygens secondary sources. Meanwhile, we have been following closely and participating modestly in the very exciting fields of metamaterials and metasurfaces. These domains of research, which were also inspired by the concepts of reflectarrays, transmit arrays, and high-impedance surfaces, were cornerstones in the development of new composite materials with properties that can be customized to the needs, exceeding by far what exist in nature [10]–[17]. The amazing results obtained in these fields greatly inspired us to transpose the concept of optical wavefront shaping in the radiofrequency (RF) world by providing us with the necessary tools to design the equivalent of a spatial light modulator (SLM) in the GHz range.

Hence, these various developments led us to use electronically reconfigurable surfaces to control electromagnetic wave propagation in scattering or reverberating media. Our idea was to propose a radio frequency passive approach where the environments are modified dynamically to optimize wave propagation between points. In other words, instead of suffering the scattering, fading and multipathing caused by wave propagation in rural or indoor channels, and complexify emitters and receivers to achieve high performances despite these problems, we proposed the solution to make the environments smart for greener and more efficient wireless communications. Originally proposed in 2012, this approach proved very difficult to get accepted by experts referring to major journals and gathered the interest of the physics community only [18].

Ten years later, taking somehow different paths, both the physics community and that of wireless communications have converged to the conclusion that RIS is becoming timely. This is why we wanted to propose a review paper dedicated to explaining where the idea of reconfigurable intelligent surfaces (RISs) came from in physics, how we see them as physicists, and where we think they can go. To that end, we will first briefly review the works performed in the wave physics community over the past decades and dedicated to wave control in complex media. We will start by introducing TR, before we describe its transposition to optics with SLMs, to finally introduce our first RIS demonstration in the microwave regime. Then, we will make the link between TR, phase conjugation, and RIS. We will explain how RIS can be used and understood simply in terms of diffraction. We will also underline how different RISs behave in free space and complex media, and make the link with holography. Finally, as pioneers of the domain, we will give our vision for the future of RIS. To do so, based on physics arguments again, we will explain how sub-6 GHz and the higher frequencies of the millimeter waves (mmWaves) differ, and how we envision RIS in both applications. We will finally discuss what is for us the main bottleneck of RIS, that is, their optimization in real time, and mention a few ideas to tackle the problem.

II. FROM TIME REVERSAL TO RIS: AN HISTORICAL POINT OF VIEW

Physicists have learned for decades to use multiple scattering of waves to focus, shape, and compress waves by controlling the many degrees of freedom offered by their propagation in these types of complex media. It was first in the field of ultrasound that our group developed in the 1990s the concept of "TR mirror" (TRM) based on the TR invariance of the wave equation to focus and control broadband waves in Multipath environments [8], [9]. After this demonstration in acoustics, we transposed the idea to the microwave domains using frequency conversions. Later on, similar experiments were performed in the optical realm using SLMs to address the many thousands of spatial degrees of freedom of light in reflection, instead of using several sources [19]. This gave us the idea to design smart surfaces whose electromagnetic properties can be modified electronically in real time to focus and control microwaves very simply for wireless communications purposes, hence ending up on the concept of RIS. We review in this first part the history of these approaches.

A. Time-Reversal Approach

The reversibility of wave propagation implies that the time-reversed version of an incident wavefield naturally refocuses on its source in any complex propagating medium. The TR technique was initially developed for broadband ultrasonic signals, with large bandwidths, resulting in fading and delay spreading through reverberation and scattering in complex environments. In its simplest realization, the TR process consists of a first forward stage in which the impulse response (or the response to a short broadband pulse) from the source to an array of

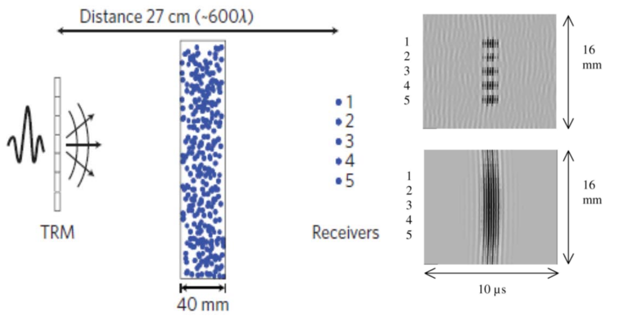

Fig. 1. *(From [23]) Left: ultrasonic TR focusing is used to focus wave spatiotemporally onto five different foci from an array of 23 antennas. Right top: result obtained in the presence of a multiply scattering medium. As the scattering medium acts as a focusing lens of great angular aperture, each 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.*

antennas (receivers) is recorded and a second backward stage in which each recording is time-reversed and then reemitted from the antenna positions. As a result of the TR invariance and of spatial reciprocity, these backward waves converge in synchrony at the original source location (spatial focusing), and the initial pulse duration is recovered (temporal compression). Hence, in terms of wireless communications, TR allows time spreading mitigation, spatial multiplexing, and security.

In a seminal work, we proposed and experimentally studied a TRM [20] implementation using ultrasonic waves in a high-order multiple scattering medium (a disordered forest of parallel steel rods in water). We showed not only that the pulse reconstruction was robust but also that compared to a homogeneous medium, it was also enhanced because of the greater effective aperture size. Remarkably, the time-reversed beam was focused to a spot much smaller (see Fig. 1) with the scattering rods than without them, i.e., in plain water!!! This result can be explained by considering that the multiple reflections in the forest redirect toward the mirror parts of the initial wave that would otherwise miss the antenna array (piezoelectric transducers). After the TR operation, the whole multiple-scattering medium acts somewhat like a focusing lens, making the mirror appear to have an aperture many times larger than its actual size and, thus, improving its resolution by a large factor. The experiment also showed that the TR process is surprisingly stable regarding signal digitization and generation. The recorded signals were sampled with analog-to-digital converters that introduced quantization errors, and even a 1-bit TR operation proved to work very well through a multiple scattering medium [21].

In fact, it was shown [22] that the spatial focusing dimension of TR can be seen as an estimator of the correlation length (the spatial correlation of the wavefield due to multiple scattering of waves), whereas the quality of the temporal compression is mainly related to the pulse bandwidth compared to the coherence frequency of the medium (frequency components of the incident source that is spaced more than the coherence frequency give uncorrelated wavefield patterns). Ultimately, in a complex medium, the spatial resolution of the reconstructed peak does not even depend on the opening of the array. Therefore, a single source SISO-TR is feasible (single-channel focusing), provided that the signals benefit from a large spectral diversity, or in other words, the bandwidth used is much larger than the correlation frequency of the medium (see Fig. 2). This TR approach can be conceived as a physical realization of matched filter working both in space and time, which maximizes the amplitude observed at the receiver location at one time for a given input energy at the transmitter.

Based on this principle, we extended the TR approach to TR communication techniques [23], and we proposed a generalization of TR to MIMO-MU schemes for ultrasonic (submillimeter wavelength) multiuser communication through a strongly multiple scattering medium. In these experiments, the propagation medium consisted of a 40-cm-large and 35-mm-thick forest made of thousands of parallel steel rods and with a 23-element array (see Fig. 1). In this context, we showed the ability of TR to focus short pulses simultaneously at five spatially distinct locations, hence realizing spatial multiplexing by harnessing multipath propagation. We also demonstrated a high information transfer rate with this space–time-matched filter technique, hence proposing in the ultrasonic range and, in 2003, the first proof of concept of massive-MIMO communications. The drawback of this technique is that, because it is a matched filter, it maximizes the amplitude received on every five locations for given input energy, but the sidelobes obtained around each focused pulse are not controlled, and they may give rise to an interference noise on each receiving antenna (similar to nonorthogonal multiple access networks). In the context of ultrasound, we proposed to compare this TR approach to a spatiotemporal inverse filter [24], [25]. It is the classical alternative that consists of measuring the complete set of responses between the base antenna and the users (the propagation operator H for each frequency), computing explicitly the inverse operator H^{-1}, and combining all the spectral components in a set of time waveforms. This spatiotemporal inverse filter permits to focus a pulse with minimal temporal and spatial side lobes. However, it is a computationally demanding method that is not always possible to implement in real time. To solve this problem, we proposed an iterative method [26] based on successive TR operations that converge to the optimal inverse filter of propagation (see Fig. 2). The basic idea is to improve the TR process by cleaning up the side lobes with an iterative process that robustly converges to the inverse filter and improves the transfer rate. It was shown subsequently [27]

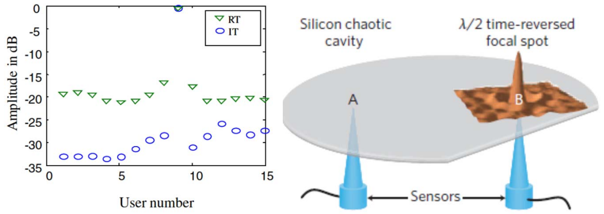

Fig. 2. *(From [27]) Left: spatial multiplexing on 15 receivers. Instead of using the classical TR approach to create 15 different beams, iterative TR converges to a regularized inverse filter, allowing spatial focusing with much lower sidelobes than TR, at the price of lower efficiency. The figure shows 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.*

that using this approach is very beneficial for wireless communications in the case of high signal to noise ratio (SNR) scenarios (classical of inverse filters), while TR is much more adapted to noisy communication channels (classical of matched filters).

All these results were initially demonstrated for ultrasonic waves propagating through multiple scattering media, but they can also be extended to any propagation with multipath as, for example, inside a reverberating cavity [28] or a waveguide [29], as demonstrated in Fig. 2. For example, simultaneous multiple spatial focusing was also studied for long-range underwater acoustic communications [30]–[34] where the ocean waveguide structure gives rise to strong reverberation and multipath.

In parallel to these various ultrasonic studies, the first TR experiment for broadband electromagnetic waves, in the 2.45-GHz band, was reported in 2004 and clearly showed the interest of TR for wideband signals (see Fig. 3), with bandwidths much larger than the coherence frequency of the medium [35], [36]. In the context of electromagnetism, it was even shown that, by introducing in the near field of the transmit antenna (at a distance smaller than the wavelength), a randomly distributed metamaterial made of a random distribution of subwavelength scatterers [37], it was possible to reduce the coherence length of the wavefield to subwavelength dimensions while shrinking its coherence frequency. This allows spatial focusing and, hence, multiplexing onto very close foci (see Fig. 3) with potential applications of this concept for MIMO-MU to improve the information transfer rate.

The various studies exemplified briefly here all take benefit of the concept of spatiotemporal degrees of freedom of a wavefield [38]. In fact, in a complex multiply scattering medium, the coherence length of the wavefield and its coherence frequency are key parameters to predict the efficiency of a focusing process. Spatial diversity is related to the number of uncorrelated antennas on the base station (separated by more than one coherence length). Frequency diversity depends on the ratio between the signal bandwidth and the coherence frequency. The product of these two quantities gives the number of spatiotemporal degrees of freedom and allows to predict the space–time concentration factor in a focusing process, whether it is intended to be used for wireless communications, imaging, or energy deposition.

Note that modern wireless communications mainly rely on OFDM techniques, where each subchannel is locally flat to mitigate the effects of fading and multipathing. TR, on the contrary, is a broadband approach that necessitates quite complicated signal acquisition and generation equipment to harness them. For narrowband signals (signal bandwidth less than the coherence bandwidth), TR can, in fact, be replaced by a much simpler operation, namely, phase conjugation. Hereby, instead of using, on each source, a time programmable transmitter, only the control of the phase and amplitude on each transmitter at the central frequency is required. This is the domain of phase-conjugate techniques that have long been used in electromagnetics at both radio and optical frequencies. Phase-conjugate electromagnetic antenna arrays were developed in the early 1960s and thoroughly studied since then [39].

B. Optical Wavefront Shaping With Spatial Light Modulators

The techniques described in the previous part all benefit from the fact that, for ultrasound as well as microwave, it is typically possible to record and synthesize waveforms over the full signal bandwidth by using arrays of transmit/receive antennas. Although this gives access to various frequency degrees of freedom, the cost of the antenna and the electronic hardware practically limits the number of spatial channels that can be addressed to tens to hundreds.

Compared to microwave and ultrasound, one limitation in the optical domain is that these complex programmable sources and receivers simply do not exist, at least as commercialized products. To solve this problem, Vellekoop and Mosk [40] in 2007 extended these concepts in the field

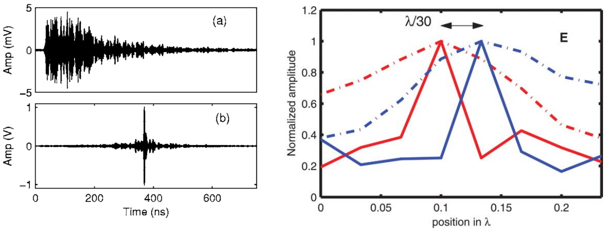

Fig. 3. *(From [35]) Left: first experimental demonstration of electromagnetic TR in a microwave cavity, showing the achieved temporal compression. (From [37]) Right: if the receiving antenna is placed in a medium made out of subwavelength spaced resonant scatterers, focal spots much thinner than half-wavelength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

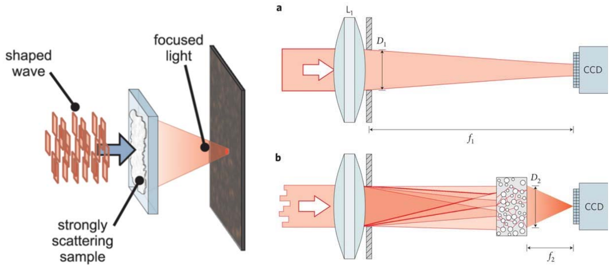

Fig. 4. ***(From [40]) Left: wavefront shaping: using arrays of pixels that control the phase of the light that they reflect, so-called SLMs; it is possible to concentrate light on a wavelength-sized focus after propagation through a thick layer of paint. (From [33]) Right: similar to TR through complex 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.***

of optical waves by introducing the concept of wavefront shaping. Wavefront shaping uses simple CCD cameras and the emergence of so-called SLMs. The latter does not offer any frequency or time control over the waves but is able to address millions of spatial degrees of freedom. Inspired from the deformable mirrors that have a small number of active elements ($\sim$100) and have been extensively used in astronomy, liquid crystal-based SLMs can work in reflection mode as controllable mirrors made of millions of pixels whose phase response can be controlled independently and continuously electronically.

Vellekoop and colleagues demonstrated that, by controlling, with a liquid crystal-based SLM, the phase of an incoming optical wavefront on many thousand spatial degrees of freedom, they were able to shape on optical wavefront to focus light through a layer of strongly scattering media (see Fig. 4), in fact, a film of white paint that scatters light in all directions. They optimized these spatial degrees of freedom with a closed-loop algorithm using as a feedback the intensity measured at the target location on a CCD camera. This method requires only a detector at the target location, and the optimization scheme is similar to deformable mirror methods in adaptive optics with the smart telescope, which compensates for phase distortions in clear air caused by turbulence. The wavefront shaping procedure used by Vellekoop and coworkers is mathematically equivalent to phase conjugation, but it is optimized through a feedback loop instead of measuring the phase of the incoming wave on all the mirror pixels.

Later, wavefront shaping was extensively studied by the same group and many others [41]–[44], and experiments very close to those realized in the realm of TR were reproduced in the optical domain, owing to this very novel and practical mean to control light. A striking example is a transposition of the experiment realized using ultrasonic TR through scattering media to optics. In this work, the authors showed how, using an SLM, they could use a thick layer of multiple scattering particles as a large lens using wavefront shaping (see Fig. 4). Meanwhile, several groups proposed various demonstrations based on these concepts, for instance, to use wavefront shaping alongside multimode fibers as optical imaging devices, to devise new ways to image deep inside biological and, hence, scattering tissues, or even to tackle quantum problems in complex media [19].

The extension of the matched filter approach described in acoustics to optics was conducted by Popoff *et al.* [45], [46]. They demonstrated the first optical measurement of over 60 000 elements of a disordered sample's transmission matrix (see Fig. 5). Light from a laser was spatially modulated by an SLM and then transmitted through a sample, using many different patterns, as in a traditional wavefront-shaping setup. A camera detected a large number of transmitted field patterns. As for optical waves, the electromagnetic field oscillates at a very high frequency (10^{15} Hz), and each pixel of the camera detects only the wavefield intensity (magnitude squared wavefield) and not the phase. Therefore, measuring also the phase information on the camera plane detector involves additional complexity, typically by interfering it with another (known) optical reference field of the same frequency, like in the process of holography. On each pixel of the camera, one measures the intensity of the interference (the interferogram), which depends on $\cos(\varphi)$, where φ is the phase difference between the incident light wavefront and the reference light. To extract exactly the phase information, the phase of the reference beam can be shifted from a known phase by moving a mirror mounted on a piezoelectric actuator. Using such interferometric methods, the phase of the transmitted modes was recovered relative to a reference at each location, hence providing a measure of the complex transmission matrix of the medium (a matrix of point-to-point transfer functions). Once the transmit matrix is known, they showed that they were able to create in parallel several beams through a scattering medium, mimicking massive-MIMO communications, and even to transmit an image through it (see Fig. 5).

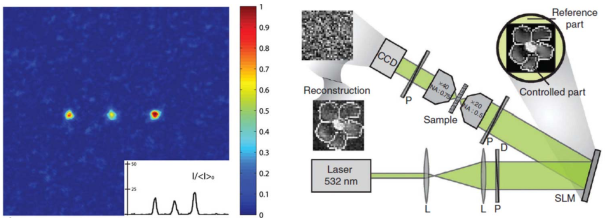

Fig. 5. ***(From [45]) Left: using the knowledge of the transmission matrix between 60 000 points on an SLM and a CCD; Popoff et al. [45] showed that they could focus light on multiple points through multiple scattering media, similar to massive-MIMO-Mu. (From [46]) Right: knowledge of such a matrix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

C. Spatial Microwave Modulator (SMM): The Ancestor of the Reflective RIS

For us, these works in optics were a real paradigm shift; indeed, instead of using several sources in order to synchronize them and focus waves in complex media, the optics community showed that it is possible to use a single and simple source and to shape waves only by controlling in a passive way how they are reflected (or transmitted) by an array of tunable elements. Hence, it gave us the idea in 2012 that the same concept could be used for microwave wireless communications. Our original idea was that, instead of using large amounts of active antennas and their complex hardware for wireless communications, as it is the case for instance in massive-MIMO, one efficient solution could be to use inexpensive passive smart mirrors with 100 or more controllable elements to shape the reflections of electromagnetic waves in such a way that they optimize wireless communications. In fact, our idea was that, if we could build these SMMs, and if they could be low cost and low consumption, we could make any environment smart to electromagnetic waves by functionalizing any surface. This, in turn, would lead to much greener wireless communications: instead of suffering from the multipath and fading from propagation channels, we would shape them for maximal data transmission at very low emitted energy.

Of course, the hardware used in the field of optics cannot be simply transposed in the context of microwaves. Deformable mirrors would require translations of the order of tens of centimeters, which are impossible to make practically let alone industrialize. Liquid crystal-based systems would require very bulky and expensive materials, and enormous energies to operate. Therefore, we had to think about how to transpose the idea of SLMs to lower frequencies, with the constraints that they are practically usable in real applications. Fortunately, we were at this time quite active in the field of metamaterials and metasurfaces, and hence, we had the idea to design electronically reconfigurable metasurfaces, which acts as SMMs. In other words, we decided to realize arrays of electronically tunable resonant unit cells, printed on conventional circuit boards and using low-consumption off-the-shelf electronic components, such as p-i-n diodes.

We realized that a tunable mirror where the phase shift is discretized with only two phases is the optimal compromise between hardware complexity and wave control capabilities [18]. Indeed, multiple phase states' unit cells induce a more complex control electronic and slower algorithms, for gains that are not very high, as we already demonstrated it in the context of TR. Therefore, we designed the first unit cell of this tunable metasurface in the following way: a passive patch antenna is backed by a grounded substrate and has a resonance frequency at the working frequency of the system, say $f0 = 2.45$ GHz. We place in the near field of this first patch a second resonator, in the form of a microstrip, whose resonance frequency is tuned from $f0$ to some much higher frequency by polarizing a p-i-n diode placed approximately in its middle. When the p-i-n diode is reverse-biased, the microstrip resonates at a very high frequency and, therefore, does not influence the main reflecting patch, which imposes a zero phase shift at the working frequency $f0$. When we forward bias the diode, the microstrip now has a resonance at $f0$ and, hence, couples with the main patch. The ensemble of two coupled resonators now has two resonances, one below $f0$ and one above $f0$, but no significant response at $f0$: the unit cell now reflects waves as a bare ground plane, imposing a phase shift of π to the incoming waves.

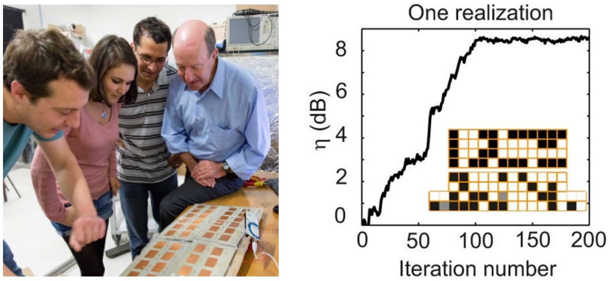

Fig. 6. ***Right: photograph from French newspaper "Le Monde" in 2014, showing the first RIS developed at the Institut Langevin for operation at 2.45 GHz to exemplify an article titled "A smart wall that dresses electromagnetic waves." (From [18]) Right: in a typical office, the electronically tunable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

To go from a single tunable unit cell to a complete tunable mirror, or SMM, we then fabricated a 104-element array of these (see Fig. 6), half-wavelength spaced, controlled by two Arduino boards. The ensemble was used to shape an existing electromagnetic wave field, using typical laboratory equipment, which is a vector network analyzer (VNA). To do so, we placed our SMM on a wall of a typical 12-m^2 office room, hence covering less than 0.4% of its total surface. We placed an isotropic antenna on one side of this room, connected to one port of the VNA, while a second one, connected to the second port of the VNA, was placed on the other side of the room and hidden from the first one by furniture. We then used the signal measured between the two antennas to calculate the energy transmitted between them and use it as feedback for a closed-loop optimization algorithm like that used in optics in the context of wavefront shaping. The result was striking: just by controlling dynamically, thanks to our SMM, 0.4% of the room's reflected electromagnetic waves, the energy transmitted from the emitting antenna to the receiving one was improved ten times on average (see Fig. 6).

Furthermore, we proved that the technology could be made mass-market compatible due to its very low complexity using very inexpensive diodes and conventional PCB technology and demonstrated that it was also energy-efficient, with the total energy consumed by the

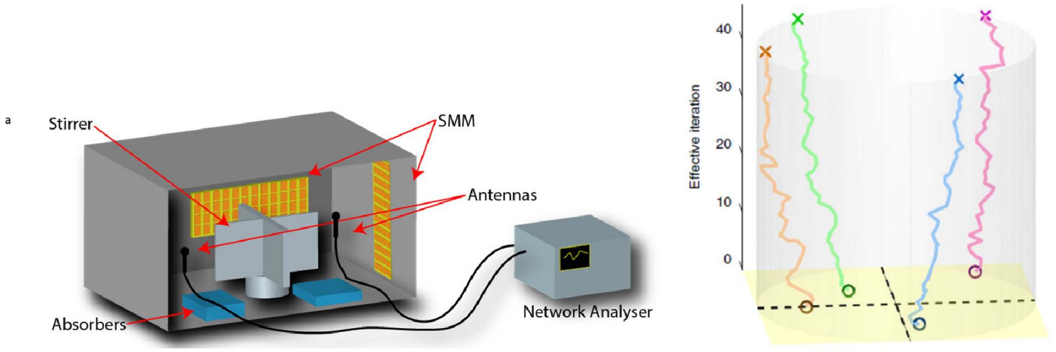

Fig. 7. *(From [47]) Left: using tunable metasurfaces or RIS as the walls of a cavity, one can design electromagnetically reconfigurable cavities with on-demand eigenmodes, for antenna applications, for instance. (From [48]) Right: RIS can also be used alongside MIMO systems to shape the communication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

104-element array being of the order of a few milliwatts. These results were first protected by a patent application in 2013 and subsequently published in 2014 (after a year of battle in other major generalist journals with experts) in a paper that can be considered the first proposal of RISs [18]. In this article, we indeed clearly opened the door to the concept of RIS by writing in the conclusion “we believe that this concept may find applications for indoor and urban wireless communications quality enhancements as we proved that the transmission between two antennas (possibly a mobile phone and a base station antenna) can be significantly increased.”

Following this pioneering demonstration, we created the startup company Greenerwave to develop products based on the concept and patent. We tried to commercialize RIS for 4G and Wi-Fi in 2016 and 2017, but, unfortunately, it was very difficult to realize convincing demonstrations on real communication systems notably due to the lack of stable feedback. Meanwhile, we continued our fundamental studies of smart electromagnetic environments using electronically tunable metasurfaces. For instance, we proved that dressing a cavity with electronically tunable metasurfaces allows to create electronically reconfigurable cavities [47] (see Fig. 7) that are now the core technology of a new generation of beamforming antennas and radars. Similarly, we pursued our research related to wireless communications in electromagnetically smart environments. An example can be found in [48] where we used a tunable metasurface in a room in order to maximize the Shannon capacity of a MIMO system (see Fig. 7). By shaping the electromagnetic waves reflected off the metasurface, we managed to optimize the rank of the MIMO channel, hence providing the first proof of concept that indoor multipathing can be controlled with RIS to unlock the full potential of MIMO systems.

III. FROM TIME REVERSAL TO RIS: A PHYSICIST POINT OF VIEW

Following the preceding review, we would like to propose a physics analysis of them. Indeed, our new approach can be interpreted as an extension of the TRM technique for focusing a wave through any complex environment, yet with much simpler hardware. As we usually work in wireless communications with narrowband signals within one coherence frequency of the medium, the analog of a TRM is a phase-conjugated mirror that we will describe. It allows a wave originating from a given antenna A to refocus back exactly on this antenna. We will show in an SISO configuration that the communication between two antennas A and B can be simply optimized by introducing a mirror (RIS) whose reflectivity is exactly the product of two phase-conjugated mirrors, respectively, associated with points A and B. This very simple theorem could allow designing an RIS that can work without exchanging information with the BS and the users. Then, we will examinate the effect of a crude binary modulated RIS on the quality of wave focusing and show that, for large surfaces, its effect is rather negligible compared to the simplicity of design that it brings. Finally, we will briefly generalize the use of RIS in the context of multiple antennas and multiple users' systems.

A. Phase-Conjugated Mirror as a Matched Filter

In a basic TR or phase-conjugated communications experiment, the intended receiver first broadcasts a pilot signal through any environment. An array of active transmit/receive antennas is used first to estimate the channel impulse responses and then sends the time-reversed or the phase-conjugated version of it back into the channel. The emitted waves backpropagate in the channel by retracing their paths and focus, at the source, the intended receiver.

For a narrowband signal of angular frequency ω, these steps can be described through a matrix formalism with matrix element $H(\vec{A}_i, \vec{B})$, describing the complex transfer function between a transmit/receive antenna located at $\vec{A}_i$ and a receiver located at $\vec{B}$. Each element of H is a complex number with amplitude $|H(\vec{A}_i, \vec{B})|$ and phase $\Phi(\vec{A}_i, \vec{B})$ depending on the relative positions of the transmit/receive antenna and the receiver and on

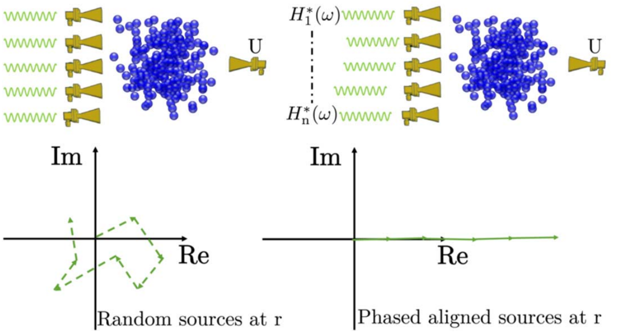

Fig. 8. *Left: when a set of n monochromatic sources sends waves in synchrony through a complex medium, the wave field at a given location can be seen as a sum of random phasors, and the resulting signal picked at this location if a random walk on the complex plane of extension n in energy. Right: using 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.

multipath encountered through the propagation in a complex medium. Note that, due to spatial reciprocity, $H(\vec{A}_i, \vec{B}) = H(\vec{B}, \vec{A}_i)$. In free space, the amplitude can be considered as nearly constant and the phase law $\Phi(\vec{A}_i, \vec{B}) = k|A_iB|$ with k the wave vector reduced to a spherical law. In the presence of multiply scattering medium, the amplitude and the phase of H become random (see Fig. 8) with a typical coherence length that described the so-called speckle size [41].

For example, in the multiple input single output (MISO) configuration, to maximize the signal amplitude on the receiver $\vec{B}$ for a given emitted energy, the transmit/receive array has to be driven by the phase-conjugated signals $H^*(\vec{A}_i, \vec{B})$ to create a constructive interference of all the emitted signals at location $\vec{B}$

$$\sum_i H\left(\vec{A}_i, \vec{B}\right) H^*\left(\vec{A}_i, \vec{B}\right) = \sum_i \left|H\left(\vec{A}_i, \vec{B}\right)\right|^2. \qquad (1)$$

It is a coherent sum of positive numbers (see Fig. 8). Note that the signals received at another location $\vec{C}$ are no more in phase resulting in a weaker amplitude. In free space, the focal spot size and the focusing efficiency depend on the angular array aperture and the number of transmit antennas. To be efficient, MISO communications require typically several active antennas with complex electronic circuitry. Moreover, the spectral efficiency can be very limited if the base station is far from the receiver, and if microwave propagation is in free space due to very poor spatial multiplexing. As we have discussed earlier, medium complexity can play an important role to achieve a better focus through spatial diversity by reducing the coherence length of the medium. However, medium complexity is not always sufficient to obtain a good focus.

B. SISO-RIS as the Product of Two-Phase-Conjugated Mirrors

To obtain a better communication performance with a limited number of transmitters, our initial idea was to replace the numerous transmit antennas with only a smart modification of the wireless environment by physically shaping the propagation medium to achieve optimal focusing through large spatial diversity.

To understand the connection between the RIS approach and the phase-conjugated approach, one can introduce in an SISO experiment a passive mirror made of many individual elements whose reflectivity can be controlled pixel by pixel and is described by a complex reflectance law $R(\vec{P}_i) = |R(\vec{P}_i)| \exp(j\phi(\vec{P}_i))$ with $\vec{P}_i$ being the pixel coordinate.

The ideal environment to maximize the amplitude received on antenna $\vec{B}$ for a given emitted energy from $\vec{A}$ would be to be located inside a perfectly reflecting ellipsoidal room with $\vec{A}$ and $\vec{B}$ at the two foci (see Fig. 9). Even if the distance between the two antennas is large, the amplitude of the signal on the receiver can be huge because the role of the ellipsoidal room is to put in phase all the rays originating from point $\vec{A}$ reflected by the room boundary and received at $\vec{B}$. However, usually, we cannot control the room shape. However, as such a process is a phase-matching process, it can be realized by introducing in any room an RIS whose reflectivity is electronically controlled to mimic an ellipsoidal room. If we are able to estimate the channels between the two antennas $\vec{A}$ and $\vec{B}$ and each pixel location by measuring the gain $H(\vec{P}_i, \vec{A}), H(\vec{P}_i, \vec{B})$. These matrix elements are complex number with, respectively, phases $\phi_A(\vec{P}_i), \phi_B(\vec{P}_i)$ and amplitude $A(\vec{P}_i), B(\vec{P}_i)$.

Once we know these matrix elements, we can design a mirror that redirects all the rays from A to B by interacting with the RIS (see Fig. 8). The phase-matching condition

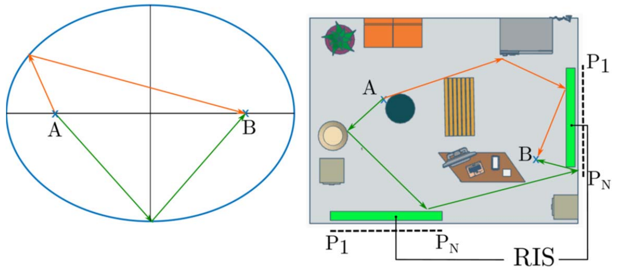

Fig. 9. *Left: very illustrative way of thinking about RIS is to consider waves propagating in an ellipse: if the emitter A and the receiver B or both placed at the foci of the ellipse, then any wave coming from A reaches B in synchrony, and vice versa, resulting in maximum energy transmission. Right: 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.*

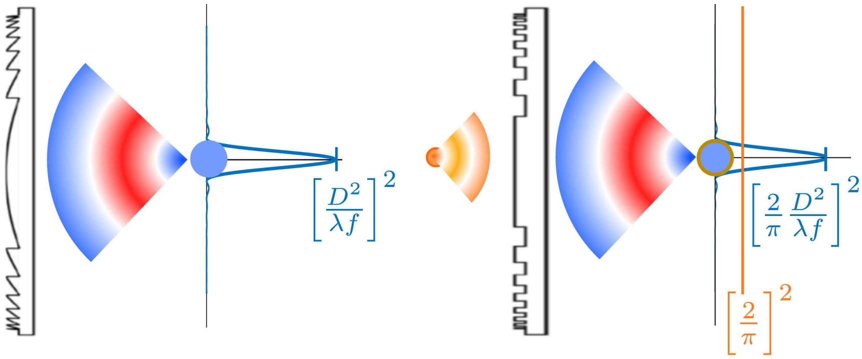

Fig. 10. *Left: similar to a lens, an RIS with a continuous phase control profile can focus waves at a distance with a resolution imposed by its typical size and the focal distance, giving a compression gain in energy. Right: difference between the previous continuous phase RIS and a binary discretized 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.*

implies that the mirror reflectivity has to be

$$\begin{aligned} R\left(\vec{P}_i\right) &= {}^{*}\left(\vec{P}_i,\vec{A}\right) H^{*}\left(\vec{P}_i,\vec{B}\right) \\ &= A\left(\vec{P}_i\right) B_i\left(\vec{P}\right) \exp\left(-j\left(\phi_A\left(\vec{P}_i\right)+\phi_B\left(\vec{P}_i\right)\right)\right). \end{aligned} \tag{2}$$

Therefore, the optimal mirror reflectivity is the **product** of the reflectivities of two different phase-conjugated mirrors, each associated, respectively, to antennas A and B. Note that, in the propagation, you can have also another wave going from A to B without interacting with the RIS. It may be a line-of-sight contribution but also a wave coming from various paths that do not interact with the smart mirror. This direct contribution can reach point B with some amplitudes and phases ϕ. To match the phase of the direct contribution to the RIS contribution, you will have to add to the RIS reflectivity a global phase contribution that matches this phase, giving rise to an RIS reflectivity equal to

$$\begin{aligned} R\left(\vec{P}_i\right) &= H^{*}\left(\vec{P}_i,\vec{A}\right) H^{*}\left(\vec{P}_i,\vec{B}\right) \\ &= \left(\vec{P}_i\right) B\left(\vec{P}_i\right) \exp\left(-j\left(\phi_A\left(\vec{P}_i\right)+\phi_B\left(\vec{P}_i\right)-\phi\right)\right). \end{aligned} \tag{3}$$

Note that the reflectivity can be simplified by considering that the amplitude factor on the reflectivity is not important, and a **phase only mirror** with $R(\vec{P}_i) = \exp(-j(\phi_A(\vec{P}_i)+\phi_B(\vec{P}_i))-\phi)$ will also focus efficiently on $\vec{B}$.

C. Binary Phase-Modulated Mirror

The main assumption is to use only a binary-phase discretization of the reflectance. This results in a huge hardware and software simplification, but it can degrade the focusing quality. In the following, we will show that, if the mirror contains enough Fresnel zones in its aperture, the degradation is limited, and nice focusing is obtained. To understand the effect of such a phase sampling on the mirror focusing properties, we have to recall both the way a converging mirror works.

Let us first consider a phase-conjugated mirror working in free space with a square aperture $D \times D$ matched to an antenna located along the mirror's central axis at a depth f. As the reflectance is phase-matched to this point, it is described by phase-modulated laws that read

$$\begin{aligned} R(x,y) &= \exp(j\phi) \\ &= \exp\left(-jk(\sqrt{f^2+(x^2+y^2)}-f^2)\right) O(x,y) \end{aligned} \tag{4}$$

with k being the wave vector and $O(x,y)$ the aperture function of the mirror (for example, a square mirror of aperture). Here, we defined the aperture as a continuous function of x and y that represent the coordinates of each RIS pixel $\vec{P}_i$. Note that, here, to simplify, we do not take into account the spatial sampling of the aperture with periodic sampling of half-wavelength pitch (as the sampling is fine enough to avoid grating lobes in the focal plane).

Neglecting a phase constant, a parabolic approximation (Fresnel approximation) reduces the reflectance law to a parabolic phase law $\phi(x,y) = -j\alpha(x^2+y^2)$ with $\alpha = \pi/\lambda f$ and λ being the wavelength.

Such a converging mirror is matched to a distance f, it reflects an incoming wave of amplitude 1 into a converging wave that concentrates into a focal spot of amplitude $D^2/\lambda f$. This focus gain is due to the fact that all the incoming energy on the mirror surface is concentrated into a focal spot whose lateral dimension is given by $\lambda f/D$ (the classical formula for a lens due to the fact that the field in the focal plane is the Fourier transform of the square aperture) [49]. Note that this phase law is defined modulo 2π and contains (see Fig. 10) a certain number of circular Fresnel zones (the phase difference $\delta\phi$ between two consecutive Fresnel zones is equal to π with radius $r_n = \sqrt{n\lambda f}$, where n is an integer that defines the Fresnel zone number). Therefore, the compression factor $D^2/\lambda f$ of such a converging mirror is equal to four times the number of Fresnel zones contained in the mirror aperture.

The effect of replacing this phase law with a two-state phase sampling results in a new reflectance law

$$\begin{aligned} \Pi_2(\phi) &= 1 \qquad -\pi/2 < \phi \le \pi/2 \bmod (2\pi) \\ \Pi_2(\phi) &= -1 \qquad \pi/2 < \phi \le 3\pi/2 \bmod (2\pi). \end{aligned} \tag{5}$$

A Fourier decomposition in terms of $\exp(nj\phi)$ gives

$$\begin{aligned} \Pi_2(\phi) &= \frac{2}{\pi}\sum_{m=0}^{\infty}\left(\frac{(-1)^{m}}{2m+1}\right) \\ &\quad \times \left[\exp\left(j\left(2m+1\right)\phi\right) + \exp\left(-j\left(2m+1\right)\phi\right)\right] \\ &\approx \frac{2}{\pi}\left[\exp\left(j\phi\right) + \exp\left(-j\phi\right)\right]. \end{aligned} \tag{6}$$

Note that the reflectance of such a mirror is the sum of the reflectance of a set of mirrors: one is the initial converging mirror $\exp(j\phi)$ with a focal distance *f*, with a second one $\exp(-j\phi)$ as a first parasitic diverging mirror with a focal distance $-f$ and many others converging and diverging mirrors with focal distances $+f/3, -f/3, +f/5, -f/5, \ldots$).

The contributions in the focal plane of all the parasitic mirrors of smaller focal distances decrease because of the ponderation factor $(-1)^m/(2m+1)$ and the geometrical wave spreading.

Therefore, the main effects of a two-state phase sampling mirror are a loss of amplitude of $2/\pi$ combined with parasitic waves that create a background noise. As the main parasitic wave comes from a virtual point located behind the mirror at a distance *-f* and contains the same energy as the converging wave, it contributes in the focal plane to a background noise amplitude equal to $(2/\pi)1/2$ that has to be compared to the amplitude of the focusing peak $(2/\pi)D^2/\lambda f$.

Thus, the ratio R of the peak amplitude to the background noise due to 2 phase sampling discretization is equal to $R = 2D^2/\lambda f$ (see Fig. 10). For example, for an aperture $D = 20\lambda$, and a focal distance $f = 40\lambda$, R equals 20, showing that the side lobes' level remains quite negligible.

The same approach can be extended to predict the effects of a two-phase discretization with the double-phase-conjugated mirror used to focus from A to B. In this case, the RIS is matched to an ellipsoidal focusing instead of a spherical focusing. The Fresnel zones are no more circular but have an elliptical shape, and their sizes and number depend on the relative positions between antennas A and B, and the RIS. Let us assume that we are in free space, and the distance between the transmit and receive antennas A and B, and each RIS pixel located at $\vec{P}_i$ are $|AP_i|$ and $|BP_i|$, respectively. To obtain the characteristics of the Fresnel zones, note that the surface of the zone is delimited by all points for which the phase difference between the direct wave and the reflected wave is the constant *np*

$$\phi_A\left(\vec{P}_i\right) + \phi_B\left(\vec{P}_i\right) - \phi = k\left(|AP_i| + |BP_i|\right) - \phi = n\pi. \tag{7}$$

Assuming that the parabolic approximation is valid, the Fresnel zones coordinates x_n and y_n in the RIS plane can be described by a set of ellipses described by

$$\begin{aligned} \alpha\left[(x_A - x_n)^2 + (y_A - y_n)^2\right] + \beta\left[(x_B - x_n)^2 + (y_B - y_n)^2\right] \\ = n\pi - \phi - k\left(z_A + z_B\right) \end{aligned} \tag{8}$$

with $\alpha = \pi/\lambda z_A$, $\beta = \pi/\lambda z_B$, and (x_A, y_A, z_A), (x_B, y_B, z_B) being the antenna coordinates.

Here, also, the RIS focusing efficiency depends on the number of ellipsoidal Fresnel zones, and the compression factor is typically four times the number of Fresnel zones.

D. RIS in Reverberating and Multiply Scattering Medium

Instead of using RIS in free space, one works in a medium with multiple scattering and multipath like a complex environment as an office full of obstacles; the number of Fresnel zones can increase significantly. In fact, in such a reverberant regime, the wavefield originated from each antenna $H(\vec{P}_i, \vec{A})$ or $H(\vec{P}_i, \vec{B})$ is no more a spherical wavefield whose phase oscillates slowly (see Fig. 11), but it becomes a random speckle wavefield where the phase and amplitude oscillate very quickly, on a distance equal to the coherence length of the medium (see Fig. 11). For example, in a chaotic reverberating room, the coherence length can be of the order of half-wavelength, and the number of Fresnel zones in the RIS aperture increases resulting in reduced side lobes and better focusing, as it was described in [18] and can be seen in Fig. 11. This effect is similar to the one described with the TR technique in multiply scattering medium where the size of the focal spot and the focusing compression is linked to the coherence length of the medium instead of the mirror aperture.

E. Connection With Holography in Free Space

In the double-phase-conjugated mirrors' approach, one has first to measure on each RIS pixel the exact field $H(\vec{P}_i, \vec{A})$ and $H(\vec{P}_i, \vec{B})$ or at least the phase law associated with each antenna. Phase detection on each pixel implies some hardware and complexifies the RIS structure. Is it possible to replace a phase detection on each pixel by an intensity measurement that is easier to achieve? A holographic point of view may be the answer at least if one works in free space (see Figure 12). This idea is connected to the way one measures in optics the phase of an incident wave by interferometry (see Section II-B).

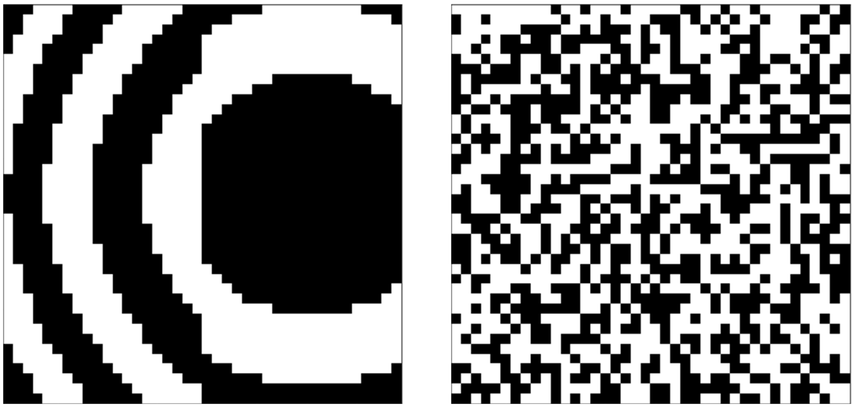

Fig. 11. *Left: typical control pattern imposed to an RIS in order to realize beamforming to a couple of far-field located points (white diode reverse and black diode forward). Fresnel zones are clearly visible. Right: control pattern imposed to an RIS after optimization in a complex scattering medium. 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.*

Imagine that the two antennas A and B are emitting in synchrony a sinusoidal wave (within a constant phase difference). The intensity $I(\vec{P}_i)$ observed on the RIS plane will results on the interference between these two waves and writes

$$I\left(\vec{P}_i\right) = A\left(\vec{P}_i\right)^2 + B\left(\vec{P}_i\right)^2 + 2A\left(\vec{P}_i\right) B\left(\vec{P}_i\right) \times \cos\left(\phi_A\left(\vec{P}_i\right) - \phi_B\left(\vec{P}_i\right)\right). \quad (9)$$

This hologram resulting from the interference between the two waves has a spatial amplitude modulation described by the cosine of a phase term that is the difference between $\phi_A(\vec{P}_i)$ and $\phi_B(\vec{P}_i)$. Therefore, the figures of constant phase in the RIS plane are, in free space, a set of hyperbolas that verify

$$\phi_A\left(\vec{P}_i\right) - \phi_B\left(\vec{P}_i\right) - \phi = k\left(|AP_i| - |BP_i|\right) - \phi = n\pi. \quad (10)$$

This defined a family of points $\vec{P}_i$ along with a set of hyperbolas that can be observed when recording the intensity modulation of the hologram. Therefore, one can imagine, from this measurement, simple algorithms that can transform these hyperbolas into ellipses and simplifies the optimization procedure. This is a subject under study.

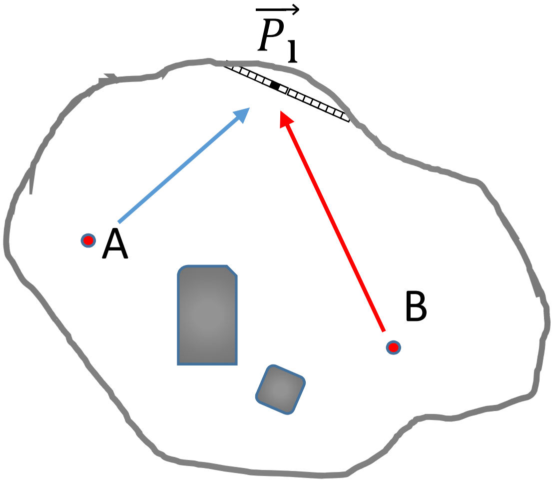

Fig. 12. *Holographic point of view. The two waves originating from antenna A and antenna B interfere on the RIS plane where the coordinates of each pixel is $\vec{P}_i$. The measured intensity pattern is, therefore, the one given by formula (9).*

F. Generalization to MISO or MIMO RIS

All the concepts described previously were introduced for SISO configuration. In SISO, the matched filter is the best solution because it maximizes the energy received on antenna B for given energy sent by antenna A. This approach can be extended for an MISO configuration with different transmit antennas allocated at various positions $\vec{A}_j$. Therefore, the mirror reflectivity for MISO will be the sum of the individual SISO mirrors

$$R_{\text{MISO}}\left(\vec{P}_i\right) = \sum_j H^*\left(\vec{P}_i, \vec{A}_j, \omega\right) H^*\left(\vec{P}_i, \vec{B}, \omega\right). \quad (11)$$

We can also use this approach in an MIMO configuration where we focus, in parallel, on an array of an antenna located at position $\vec{B}_k$. As in the active antenna MIMO configuration described in MIMO-MU with TR or phase-conjugated mirrors, a matched reflectivity to a set of antennas located at position $\vec{B}_k$ reads

$$R_{\text{MIMO}}\left(\vec{P}_i\right) = \sum_k \sum_j H^*\left(\vec{P}_i, \vec{A}_j, \omega\right) H^*\left(\vec{P}_i, \vec{B}_k, \omega\right). \quad (12)$$

However, as we noticed when we compared matched filter to the inverse filter, the matched filter is not the best approach when there are several receiving antennas. Note that such a phase-conjugated approach guarantees only that we obtained, for a given transmit energy, a maximum on each receiving antenna, but it does not guarantee that each individual focal spot will not overlap with the other spots. Side lobes can create a level of interference between each beam that may limit the Shannon capacity. If the receiving antenna is well separated, in order to guarantee that the focal spots obtained on each individual antenna do not interfere with the other receiving antenna (it means complete orthogonality), one can apply to the transmit array a superposition of the different focal laws. The results will be a maximization of the signals received on each individual antenna. In this case, there is a better approach than only a superposition of phase-conjugated beams. The matched filter approach can be replaced by an inverse filter approach that can diminish the level of interference at the expense of the amplitude level. For example, an iterative phase-conjugated procedure can converge toward an inverse filter. Such approaches are under study.

IV. FROM TIME REVERSAL TO RIS: A PIONEERS' POINT OF VIEW

Now that we have explained where the idea of RIS comes from, how we ended up working on it ten years ago, and how it behaves in terms of physics compared to more conventional approaches; it is interesting to envision the perspectives of RIS as we see them. Indeed, the topic is currently gaining a lot of momentum in the wireless communications community [50]–[63], and years of research on the topic, as well as a strong background in wave control in complex media, give us a large field of view that is necessary to foresee the possibilities of the technology and its limits. To that end, we will first discuss the potential applications of RIS at low frequencies and underline how the scattered nature of the wave fields and the RIS design at these frequencies calls for energy autonomous and wireless systems. Next, we will examinate the case of mmWave and propose a different use of RIS, which again matches both the specificity of the electronics and the wave propagation at these frequencies. Finally, we will finish this perspective part by discussing the toughest aspect of RIS, that is, its optimization procedure.

A. RIS in the Sub-6-GHz Bands: Autonomy Is a Must Have

The first proposal that we made of RIS was in the low-frequency range, namely, at the Wi-Fi frequency of 2.45 GHz. In this study, we already noticed that, if the RIS was placed rather far away from either the source or the receiver, its effect was minimized. For practical applications, it is important to understand the nature of the waves carrying the wireless information in order to plan any infrastructure based on the technology. At low frequencies, indeed, the propagation of electromagnetic waves is limited by two main physical aspects: diffraction and scattering. These fundamental aspects impose some severe limitations on RIS, which must be taken into account for any practical deployment.

The first physical effect to consider when it comes to RIS is diffraction. To understand its effect, we must put a few numbers on the problem that we tackle. Waves at sub-6 GHz have typical wavelengths of about 10 cm. Even if massive-MIMO is used on base stations, the base station antennas cannot be larger than about 1 m, for cost, visibility, and many other reasons. Given that the size of the focal spot achieved by antenna arrays is limited by diffraction to $\lambda f/D$, where f is the focal distance and D is the aperture of the antenna, and considering that base stations are typically 100 m away from the users, we can estimate that the energy emitted toward a point in space, even if beamforming is used, is spread on typical spots of several meters' diameter wide. This very simple analysis shows that, even with complex antenna systems at the base stations, RIS needs to be deployed on large surfaces if they are to collect a significant part of the energy emitted by the network. This analysis stands even more when considering the point of view of the user, which uses simple antennas radiating in all directions.

Of equal importance to the potential and limits of RIS is the effect of scattering on the waves. Indeed, most wireless communications occur in urban environments, if not indoors. In these media, walls, furniture, windows, and so on behave as strong scatterers for the incoming waves. As a result, the wave field emitted by the base stations, even if it is targeted to a given location, is very quickly scattered by the propagation medium. Consequently, the wave field tends to be very distributed in space, almost filling the environment, especially indoors. This is good since this is what allowed at first wireless communications to work, even in personal houses and the office buildings. Yet, this also means that, if RIS is to be used, they again need to be of large dimensions to control a significant amount of the electromagnetic waves used in the wireless communications and, hence, have a significant impact. They also need to be distributed in the environments in order to control as much RF energy as possible. Again, this simple observation stands even more when considering the point of view of the users, which are often within the scattering propagation medium and communicate with low directivity antennas.

Diffraction and scattering, together, plead for RIS covering large surfaces, which, at first sight, may seem very problematic. However, in fact, if we consider carefully RIS at these frequencies, these problems are not so drastic. In fact, there are several arguments that militate for large areas and numerous RISs at low frequencies. First, with the wavelengths being relatively large and RIS optimal pavement being at the half-wavelength pitch for obvious reasons, large areas do not necessarily mean an outrageous number of unit cells. Second, the simplicity of low-frequency designs and the very low cost of the available electronics at these frequencies imply that RIS can be produced for extremely low cost, using printed electronics or other techniques used for instance for RFID inlays. If such industrial approaches are applied to RIS at sub-6 GHz, prices of the order of a dollar per meter square could be envisioned, which would make the technology very competitive, even cheaper than repeaters or relays. Third, and most importantly, switching elements, such as p-i-n diodes at these frequencies, on top of being very inexpensive, consume extremely little energy, meaning that RIS can ultimately be energy autonomous.

In fact, our belief, as we claimed it, in a recent publication, is that RIS must be autonomous at these frequencies. This is perfectly achievable if one imagines RIS that harvests energy, for instance, RF energy, and is wirelessly controlled. We have recently demonstrated such kind of RIS in the context of RFID, which is both powered and controlled by the RFID reader (see Fig. 13). The transposition of this approach to cellular networks at sub-6 GHz should not be a problem and would solve any issue related to installation, cost, and global deployment of RIS. This topic is tackled in EU-funded projects that we participate in (Rise-6G and Meta Wireless).

B. RIS at mmWave: The Passive Access Point Extender

When dealing with much higher frequencies, such as 5G mmWaves at 25–30 GHz, on the other hand, things become very different. If low-frequency RF wave fields tend to be globally well-distributed, because of signal-to-noise issues, mmWave systems require line-of-sight communications. In this domain, wireless communications resemble optical links, and they face very different issues: the first one being the propagation loss, and the second one being the shadowing by objects, walls, furniture, windows, and so on.

The first problem, very linked to the aforementioned problem of diffraction, takes nonetheless its roots in a different area. Namely, at high frequencies, conventional RF components stop performing well. Above 15 GHz or so, to amplify waves, exotic semiconductors must be used, which are more expensive, rely on complex fabrication processes, and present gains that are much lower than their low-frequency counterparts. Because of this, the power amplifiers and low noise amplifiers at mmWave limit the sensitivity of the systems, a fact that must be overcome at the antenna level. These, alongside the effects of diffraction at small wavelengths, explain why beamforming is mandatory at mmWave. Considering this, one naturally understands that RIS technology must take a very different shape in this part of the spectrum. Indeed, from large surfaces covering many parts of environments, the beamforming inherent to mmWaves tends to lead to discrete and relatively small areas of RIS, distributed here and there to reflect and redirect an incoming beam, whether it is coming from a base station or from another RIS.

The second problem encountered in mmWave communications is directly linked to the way the wave propagates at high frequencies and to the beamforming techniques used. This problem, the shadowing or blockage, is simply the fact that high-frequency wave beams cannot penetrate most of the materials, including glasses, and are most of the time scattered by objects in a ballistic way, that is, in a way very similar to ray optics. As a consequence, the furniture and objects in a given environment limit drastically the ability of mmWaves to propagate therein and, therefore, to carry their data. This situation is in stark contrast to that of low-frequency waves that, while propagating in a complex medium, tend to fill it and, hence, allow some reception almost everywhere, at least on average. To fight against this blockage effect, the solution, if one does not want to install base stations every few meters especially indoors, is again to distribute small size RIS at distributed locations, in order to use beamforming from the base station and the RIS, to go around objects.

Hence, both the propagation loss and the blockage effect, which are inherently linked to high-frequency communications, plead for moderate size and judiciously placed mmWave RIS that acts as passive yet dynamically reconfigurable access point extenders. We recently demonstrated the credibility of the approach [64], [65], achieving a mmWave radio link in a nonline-of-sight configuration, using a 20 cm * 20 cm RIS at 28 GHz and 10 m away (see Fig. 14). Here, we must note that, again, physics is in line with what can be practically realized. Indeed, at high frequencies, the electronics that were very low cost at sub-6 GHz start to be more expensive, and a RIS

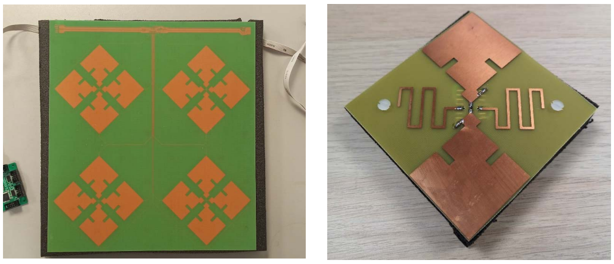

Fig. 13. *Left: conventional tunable metasurfaces, or RIS, are matrices of multiple identical pixels that contain electronic tuning components, such as p-i-n diode or varactors. These RISs are connected to a central board that is used to both power and control independently each tuning element. Here, 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.*

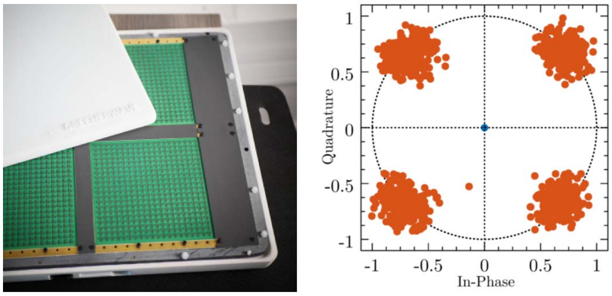

Fig. 14. *(From [65]) Left: 20 cm * 20 cm, 40*40 dual-polarized unit cell RIS containing 3200 p-i-n diodes is used as a passive mmWave access point extender at 28 GHz. (From [65]) Right: IQ diagram of the signal received, for Rx and Tx antennas in nonline-of-sight configuration and at 10 m when an RIS 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.*

contains about 100 times more unit cells for a similar size. Overall, it makes the square meter cost about 100-fold to 1000-fold more expensive than at low frequencies. In addition, switching a component at mmWave requires more energy, rendering the energy autonomous approach very difficult to realize in practice. Hence, both the technical needs and the economics push for distributed access point extenders, which can be for instance both powered and controlled by an Ethernet cable, rather than to cover large parts of the environment with RIS.

C. Common Problematic Denominator: RIS Optimization in Real Applications

In the previous parts, we underlined the limits and peculiarities of RIS at both sub-6 GHz and mmWaves, but we did not comment on the most limiting aspect of RIS. Indeed, if we mentioned the beamforming possibilities offered by RIS, we voluntarily forgot to explain how the latter was realized. Yet, this aspect is of paramount importance, as it is clearly peculiar to RIS technology. Indeed, in all previously mentioned approaches relying on active sources, whether it is TR, massive-MIMO, and so on, arrays of transceivers are used, which can estimate the channel using pilot signals, and use this information to control the emission of waves in various ways. RISs are very different in that they do not demodulate the RF signals nor get any information from them. They stay at the electromagnetic wave level, simply acting as controllable reflectors. Hence, if a RIS is part of the network between a base station and a user, there is *a priori* no way to estimate the RIS-controlled channel, at least in real time. Hence, there is no direct way to realize the beamforming or more practically to choose the good RIS configuration for the desired goal.

Again, regarding this aspect, it is important to distinguish between various cases and notably between high and low frequencies. Let us start with the case of the sub-6 GHz, which seem to be the easiest one. In this range, we have already mentioned that the RIS should be large and relatively numerous. This tends to indicate that the control of these devices will be of enormous complexity. Yet, things are different if we consider that: 1) the wave field scattered by RIS has relatively large correlation lengths, which should be the case very often if users are not in very close proximity with the RIS and 2) dynamic changes in the environment affect the RIS effect only marginally since most of it is static at the scale of the distributed wave field. In this case, which could be the case of a RIS infrastructure installed and controlled by telecom operators, it would make sense that learning approaches are used. In other words, the network could learn how to optimize the RIS configurations globally, as a function of the time, the distribution of users, and so on, using quality of service mapping and network optimization, as it is already done. Such slow varying control would not necessitate any real time nor fantastically complex algorithms and could lead to dramatic increases in the wireless spectral efficiency.

When it comes to higher frequencies, yet, things are somehow more complex. Indeed, as we already pointed it, high frequencies come with point-to-point communications and beamforming using sparse arrangements of small-size RIS. In this case, it is obvious that any movement of the user must be tracked very efficiently by the RIS, which must adapt in real time in order to provide the required gain for efficient data transmission. This problem is in our opinion still open, even if many ideas can come to mind. One simple yet technologically demanding solution is to have a closed-loop algorithm controlling the RIS, for instance, from the base station, using a real time feedback quantifying the quality of the signal received by the user. Such an approach could be doable provided that the algorithm converges faster than the user moves, which is possible in practice, at least to some extent. Other solutions are imaginable, such as using low-frequency signals or video to locate the user, and conventional beamforming weights on the RIS, assuming perfect free space propagation (a valid assumption at mmWave).

Our favorite solution relies, nevertheless, on feedback given by the user automatically (without it knowing) and in real time, which could be very easily detected by the RIS and used for self-optimization. This could be achieved, for instance, using a simple nonlinear circuit on the user device that generates a low-frequency signal from the mmWave frequency that it picks. Using this low-frequency feedback would allow the RIS to focus mmWaves on the user in real time, using a closed-loop algorithm that does not need any information from the base station. Indeed, the level of the low-frequency nonlinear signal is proportional to that of the mmWaves focused by the RIS, hence providing an easy-to-detect and instantaneous feedback. Similar approaches were demonstrated in optics to focus light deep inside scattering media using fluorescence for instance, as shown in Fig. 14 [66]. We transposed the same

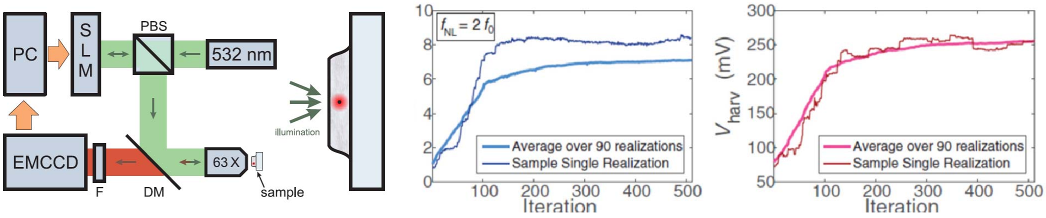

Fig. 15. ***(From [66]) Left: experimental setup used in optics to focus green light deep inside strongly scattering media using red light scattered by a fluorescent probe. (From [67]) Right: equivalent experiment in the context of wave field control using tunable metasurfaces; RIS is used in a cavity 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).***

concept to wave focusing using RIS in cavities on an RF harvesting chip (see Fig. 15) by optimizing the spurious harmonics that it was generating while harvesting Wi-Fi frequency waves [67].

V. CONCLUSION

With this article, our goal was to show how ideas incubated during decades of research in the field of physics can come to reality in the realms of wireless communications. We also wanted to highlight how mixing various fields of research always leads to out-of-the-box ideas and ultimately to very interesting applications. In the meantime, we felt obliged to give our physicist and pioneer point of view on RIS.

To that end, we have tried to give an overview of the research on wave control in complex media, concentrating on the works that have led to the invention of RIS. We have not tried to be as complete as possible, but, rather, we have chosen to limit ourselves to the few works that have really paved the way to the idea, again from the physics point of view. For instance, metamaterial and metasurface works were not discussed since they are in our opinion a tool that is used in RIS, rather than the concept of RIS.

Then, we have proposed an analysis of RIS in the light of conventional and active beamforming and focusing approaches in complex media, which are TR and phase conjugation. This has allowed us to define the physical mechanism underlying RIS and to challenge some common beliefs, such as the need for high phase control for good efficiency. Again, this part concentrated only on the physical mechanism of RIS, and any technical implementation of them has been left apart, as they are very numerous, starting from the works in the domain of reflectarrays in the 1990s, to those on metasurfaces starting after 2010.

Finally, in the last part, we have used our wave physics expertise and our long experience with RIS in order to examine in which case, and under which circumstances, RIS could be useful and a viable approach. Starting from the case of the low frequencies, we have identified a road to the massive deployment of RIS, which makes sense both in terms of physics and economics. At mmWaves, also, we have proposed a use case that reconciles the need for RIS and its practical use. We have, finally, discussed one of the major bottlenecks of the technology and its nontrivial optimization, and proposed a few ways around it for real applications.

We hope that our physicist point of view adds a stone to the massive amount of work currently devoted to RIS, and that our long experience using them gives a few answers to currently open questions in the community. ■

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