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On-Demand Perfect Absorption in Disordered Scattering Systems with Programmable Meta-Atom Inclusions

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Abstract

Waves scattered by random disordered matter are virtually never completely absorbed because the system's excitation and decay rates are not balanced. To achieve the scattering anomaly of perfect absorption (PA), we propose to tweak the disordered system's scattering properties such that a scattering matrix zero becomes real-valued. We experimentally demonstrate our approach for electromagnetic waves trapped inside a 3D chaotic cavity doped with meta-atom inclusions that can be programmed individually to tune the system's scattering properties. We systematically investigate the achievability and extreme sensitivity of PA in disordered structures. Finally, we leverage the unique properties of our technique to demonstrate an application to physically secure wireless backscatter communication.

1 Introduction

The goal of fabricating materials capable of perfectly absorbing an incident wave is an old problem in material science. It requires perfect matching of the excitation and attenuation rate of a resonant material. A vast body of literature explores the possibility of carefully engineering a perfectly absorbing metamaterial satisfying this condition [1]–[7]. If a single channel delivers the incident radiation, the problem is also known as "critical coupling". The PA scattering anomaly can be understood in terms of the analytical properties of the system's scattering matrix: at the PA condition, one of its zeros is real-valued, that is, it lies on the horizontal frequency axis [8]. The extreme sensitivity of the PA condition to any sort of detuning is at the origin of its technological potential in sensing, wave filtering, etc.

Recently, a variant of this old problem caught the material and wave engineering communities' interest: what about perfect absorption by a material that is not carefully fabricated but completely disordered? [9], [10] Indeed, given the generality of the scattering-matrix formalism, in principle, PA with disordered matter is not impossible. In practice, however, it is extremely unlikely given the vanishing probability that the disordered material's structure and distribution of loss can satisfy the PA condition. A recently proposed technique to observe PA in a disordered system scanned a large multi-dimensional parameter space involving the shape of the incident radiation, the operating frequency as well as the system's attenuation rate [11], [12].

Here, we put forth a completely different approach, which merely relies on adjusting some details of the complex scattering inside the disordered matter by doping the latter with programmable meta-atom inclusions whose scattering properties can be optimized in situ [13]. We experimentally validate our technique in a 3D chaotic cavity. The "on-demand" nature of our approach enables a thorough experimental investigation of the statistical properties of PA in disordered matter as well as the first technological application based on the phenomenon: physically secure wireless backscatter communication.

2 Achievability of PA in Disordered Matter

We consider the chaotic cavity seen in Fig. 1(a) as disordered system that is excited by a single channel, such that PA corresponds to zero reflected power P_{out}/P_{in}. To tune the system's scattering properties, the 16-element programmable metasurface [14], [15] seen in Fig. 1(b) is used; each meta-atom's electromagnetic response can be controlled individually to mimic a perfect electric or magnetic conductor at its operating frequency in the vicinity of 20 GHz. In a disordered system, the reflected power is a statistically distributed quantity: different realizations of the system's disorder (e.g. via a frequency sweep) can be interpreted as drawing a "new" value from the distribution. "Accidently" coming across near-zero values is extremely unlikely, as evidence by the experimentally obtained cumulative distribution function (CDF, see blue curve in Fig. 2). Our idea is to drastically increase this probability by judiciously programming the meta-atoms, such that the probability of observing PA becomes tangible. Indeed, in our experiment it increases by four orders of magnitude from 7.5×10^{-6} to 5.3×10^{-2} (for practical convenience, we define PA as $P_{out}/P_{in} < 2.5 \times 10^{-7}$) – see the blue and red curves in Fig. 2. Specifically, we observe more than 150 frequencies within the considered range at which PA can be implemented "on demand" by choosing the appropriate configuration of the meta-atoms. In our system we cannot achieve PA at every desired frequency because (i) the meta-atoms' frequency response is not flat and at certain frequencies their impact on the field is weaker; and (ii) the number of zeros in the vicinity of a given frequency is

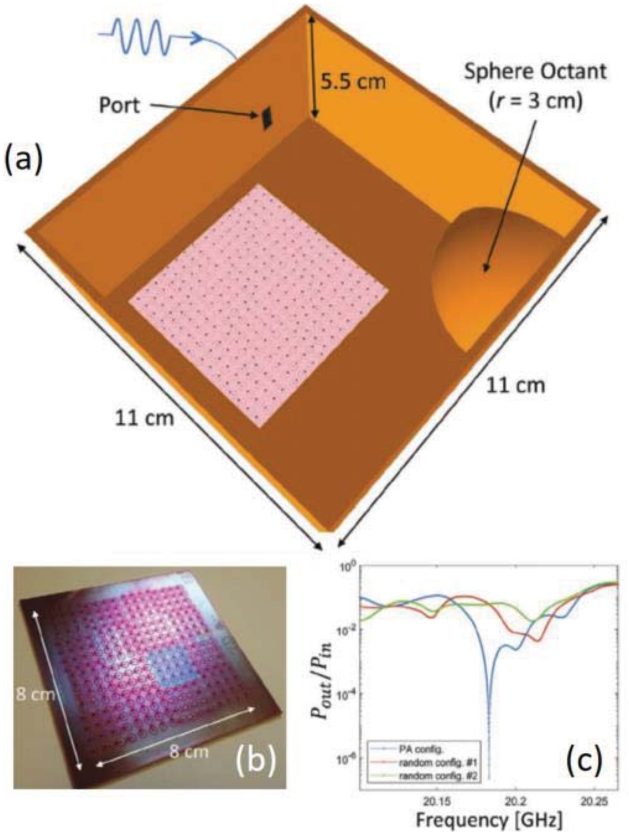

Figure 1. (a) Experimental setup involving a disordered 3D chaotic cavity excited by a single channel (coax waveguide). One wall is equipped with a 16-element programmable metasurface. (b) Photograhic image of the metasurface. (c) Experimentally measured reflected power for the metasurface configuration yielding PA at 20.18 GHz as well as for two random configurations.

very likely not constant. To enhance the achievability of PA, multi-bit instead of 1-bit programmable meta-atoms can be employed and the total number of meta-atoms can be increased. Indeed, the yellow, purple and green curves evidence the opposite: reducing the number of meta-atoms deteriorates the achievability of PA.

3 Sensitivity

The very narrow reflectance dip in Fig. 1(c) already hints at the extreme sensitivity of the PA condition. Since this sensitivity is crucial for the concept's technological relevance, here we systematically study the impact of geometry and frequency detuning on the PA condition. We conveniently implement geometry detuning by tuning the configuration of one meta-atom away from that imposed by the optimal configuration. Fig. 3(a) shows that detuning a single pixel already completely destroys the PA condition, resulting in an increase of power by 40 to 50 dB. (Note that pixels 1 and 2 had a technical defect in the experiment.) Fig. 3(b) shows that frequency detuning by a few MHz is also sufficient to completely destroy the PA condition. A few MHz is at least an order of magnitude below the spectrum's characteristic correlation frequency and four orders of magnitude smaller than the PA frequency itself. We faithfully expect further sensitivities, e.g. to the port's spatial position, but these are not easily observed in experiments.

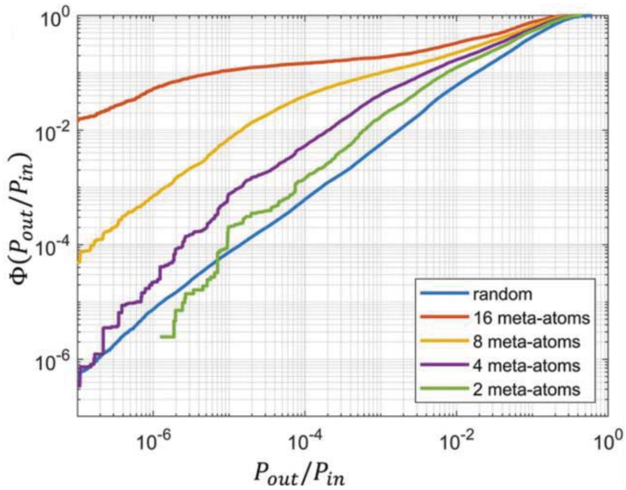

Figure 2. Experimentally determined CDF $\Phi(P_{out}/P_{in})$. The blue curve is based on the 19 – 24 GHz band and all possible metasurface configurations. The remaining lines consider for each frequency point only the reflected power corresponding to the optimal metasurface configuration, for different numbers of programmable meta-atoms.

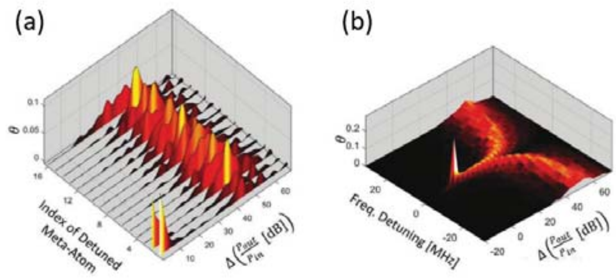

Figure 3. (a) For each meta-atom, the probability density function θ of the change of P_{out}/P_{in} on a logarithmic scale upon detuning is shown, evaluated based on the 168 frequencies for which $P_{out}/P_{in} < 10^{-6}$. (b) θ for each considered frequency-detuning strength.

4 Application to Secure Communication

We now leverage the unique "on demand" feature of our technique as well as the extreme sensitivity of PA established in the previous section to propose a physically secure scheme for wireless communication. Indeed, the scheme we propose is secure on the hardware level such that no data encryption is needed: communication can only take place if its physical security is guaranteed. Unlike conventional communication systems in which Alice actively generates and modulates waves to transfer information to Bob, in our scheme Alice only controls the metasurface configuration and thereby the scattering properties of the propagation environment – see Fig. 4(a). Bob emits waves in order to monitor the reflected power spectrum on his port. In order to transfer information to Bob, Alice configures the propagation environment to switch PA on and off at Bob's port.

We focus in the following on the case of an eavesdropper Eve being part of the communication system since the beginning because if she appeared during operation, Eve's presence would detune the geometry and destroy PA, revealing her presence. If Alice transfers information to Bob by alternating between the special PA configuration and a random one, or between two PA configurations for two distinct frequencies, Eve could capture most of the transferred information. Indeed, although PA is only observable on Bob's port, with a high dynamic range Eve could detect the switching between two fixed configurations and decode the binary message up to a confusion regarding which configuration is "1" and which is "0". However, as shown in Fig. 4(b), our technique enables "on demand" PA at several frequencies, so "1" (resp. "0") can be defined as creating a PA (resp. nonPA) condition for Bob's port at a randomly chosen frequency.

Eve can either monitor her own port's reflection spectrum or the energy that Bob radiates as he monitors his own port's spectrum. Upon visual inspection, neither of these two quantities shown in Fig. 4(c) contains the information transmitted from Alice to Bob. The physical security of our scheme is also confirmed via a self-supervised artificial neural network auto-encoder: while the data measured by Bob is easily clustered into two groups corresponding to "1" and "0", the same is not true for the measurements that Eve can make. Hence Bob correctly receives all bits whereas Eve can only measure a series of random signals irrespective of her dynamic range. Bob could add a further level of security by varying the incident field he uses over time.

5 Summary

We proposed and experimentally demonstrated a route to achieving PA "on demand" in disordered matter solely by tuning its disorder with programmable meta-atom inclusions [13]. Looking forward, our demonstration for a single-channel scenario can be generalized to multiple excitation channels ("coherent PA", CPA) [16], [17]. Our method can then also be expanded to achieve CPA with any fixed arbitrary injected wavefront [18]. Besides the reported technological promise held in the area of secure communication [13], other applications include wave filtering and precision sensing. From a theoretical point of view, the extreme sensitivity of the PA scattering anomaly

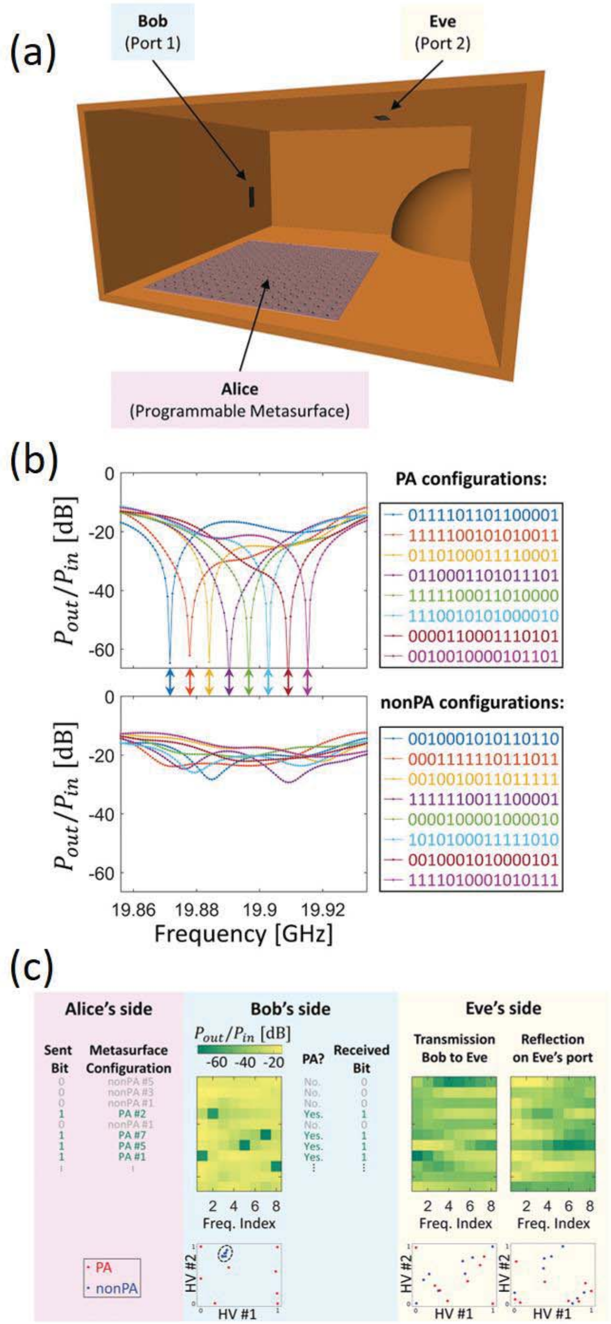

Figure 4. (a) Experimental setup identifying Alice (controls the metasurface), Bob (controls port 1) and Eve (controls port 2). (b) Selection of eight metasurface configurations yielding PA at eight corresponding frequencies (indicated with arrows) as well as eight configurations not yielding PA at these frequencies. (c) In situ measurements of information transfer from Alice to Bob using randomly chosen PA (nonPA) configurations out of those identified in (a) to encode "1" ("0"). The signals that Eve can monitor are also shown. An autoencoder-based analysis clearly clusters PA and nonPA configurations in the 2D hidden variable (HV) space based on Bob's measurements, but not based on Eve's measurements.

can be related to the associated divergence of the time delay [17].

6 References

[1] R. L. Fante and M. T. McCormack, “Reflection properties of the Salisbury screen,” *IEEE Trans. Antennas Propag.*, vol. 36, no. 10, Art. no. 10, Oct. 1988, doi: 10.1109/8.8632.

[2] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, “Perfect Metamaterial Absorber,” *Phys. Rev. Lett.*, vol. 100, no. 20, Art. no. 20, May 2008, doi: 10.1103/PhysRevLett.100.207402.

[3] Y. D. Chong, L. Ge, H. Cao, and A. D. Stone, “Coherent Perfect Absorbers: Time-Reversed Lasers,” *Phys. Rev. Lett.*, vol. 105, no. 5, Art. no. 5, Jul. 2010, doi: 10.1103/PhysRevLett.105.053901.

[4] W. Wan, Y. Chong, L. Ge, H. Noh, A. D. Stone, and H. Cao, “Time-reversed lasing and interferometric control of absorption,” *Science*, vol. 331, no. 6019, Art. no. 6019, 2011, doi: 10.1126/science.1200735.

[5] C. M. Watts, X. Liu, and W. J. Padilla, “Metamaterial Electromagnetic Wave Absorbers,” *Adv. Mater.*, vol. 24, no. 23, Art. no. 23, Jun. 2012, doi: 10.1002/adma.201200674.

[6] V. S. Asadchy, I. A. Faniayeu, Y. Ra’di, S. A. Khakhomov, I. V. Semchenko, and S. A. Tretyakov, “Broadband Reflectionless Metasheets: Frequency-Selective Transmission and Perfect Absorption,” *Phys. Rev. X*, vol. 5, no. 3, Art. no. 3, Jul. 2015, doi: 10.1103/PhysRevX.5.031005.

[7] D. G. Baranov, A. Krasnok, T. Shegai, A. Alù, and Y. Chong, “Coherent perfect absorbers: linear control of light with light,” *Nat. Rev. Mater.*, vol. 2, no. 12, Art. no. 12, Dec. 2017, doi: 10.1038/natrevmats.2017.64.

[8] A. Krasnok, D. Baranov, H. Li, M.-A. Miri, F. Monticone, and A. Alú, “Anomalies in light scattering,” *Adv. Opt. Photonics*, vol. 11, no. 4, Art. no. 4, Dec. 2019, doi: 10.1364/AOP.11.000892.

[9] Y. V. Fyodorov, D. V. Savin, and H.-J. Sommers, “Scattering, reflection and impedance of waves in chaotic and disordered systems with absorption,” *J. Phys. Math. Gen.*, vol. 38, no. 49, Art. no. 49, Dec. 2005, doi: 10.1088/0305-4470/38/49/017.

[10] H. Li, S. Suwunnarat, R. Fleischmann, H. Schanz, and T. Kottos, “Random Matrix Theory Approach to Chaotic Coherent Perfect Absorbers,” *Phys. Rev. Lett.*, vol. 118, no. 4, Art. no. 4, Jan. 2017, doi: 10.1103/PhysRevLett.118.044101.

[11] K. Pichler *et al.*, “Random anti-lasing through coherent perfect absorption in a disordered medium,” *Nature*, vol. 567, no. 7748, Art. no. 7748, Mar. 2019, doi: 10.1038/s41586-019-0971-3.

[12] L. Chen, T. Kottos, and S. M. Anlage, “Perfect absorption in complex scattering systems with or without hidden symmetries,” *Nat. Commun.*, vol. 11, no. 1, Art. no. 1, Dec. 2020, doi: 10.1038/s41467-020-19645-5.

[13] M. F. Imani, D. R. Smith, and P. del Hougne, “Perfect Absorption in a Disordered Medium with Programmable Meta-Atom Inclusions,” *Adv. Funct. Mater.*, no. 30, Art. no. 2005310, Sep. 2020, doi: 10.1002/adfm.202005310.

[14] T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, and Q. Cheng, “Coding metamaterials, digital metamaterials and programmable metamaterials,” *Light Sci. Appl.*, vol. 3, no. 10, Art. no. 10, Oct. 2014, doi: 10.1038/lsa.2014.99.

[15] T. Sleasman, M. F. Imani, J. N. Gollub, and D. R. Smith, “Microwave Imaging Using a Disordered Cavity with a Dynamically Tunable Impedance Surface,” *Phys. Rev. Appl.*, vol. 6, no. 5, Art. no. 5, Nov. 2016, doi: 10.1103/PhysRevApplied.6.054019.

[16] B. W. Frazier, T. M. Antonsen, S. M. Anlage, and E. Ott, “Wavefront shaping with a tunable metasurface: Creating cold spots and coherent perfect absorption at arbitrary frequencies,” *Phys. Rev. Res.*, vol. 2, no. 4, p. 043422, Dec. 2020, doi: 10.1103/PhysRevResearch.2.043422.

[17] P. del Hougne, K. B. Yeo, P. Besnier, and M. Davy, “On-demand coherent perfect absorption in complex scattering systems: time delay divergence and enhanced sensitivity to perturbations,” *arXiv:2010.06438*, Sep. 2020.

[18] P. del Hougne, K. B. Yeo, P. Besnier, and M. Davy, “Programmable meta-atom inclusions in complex media enable coherent wave control with an arbitrary wavefront,” *arXiv:2011.04514*, Oct. 2020.