Massively degenerate coherent perfect absorber for arbitrary wavefronts

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One of the key insights of non-Hermitian photonics is that well-established concepts such as the laser can be operated in reverse to realize a coherent perfect absorber (CPA). Although conceptually appealing, such CPAs are limited so far to a single, judiciously shaped wavefront or mode. Here, we demonstrate how this limitation can be overcome by time-reversing a degenerate cavity laser based on a unique cavity that self-images any incident light field onto itself. Placing a weak, critically coupled absorber into this cavity, any incoming wavefront, even a complex and dynamically varying speckle pattern, is absorbed with close to perfect efficiency in a massively parallel interference process. These characteristics open up interesting new possibilities for applications in light harvesting, energy delivery, light control, and imaging.

The absorption of light is a fundamental process in nature, physics, and engineering that is central to many important tasks ranging from photosynthesis to the operation of solar panels and detectors. Whereas light is readily absorbed by thick materials that we perceive as black, thin and weakly absorbing media are inherently far less efficient in capturing incoming radiation and converting it into heat or other forms of energy. A well-known strategy to make even such weakly dissipative substances strongly absorbing is to embed them into a resonant structure. At the so-called critical coupling condition, where the coupling strength to such a resonator is exactly balanced with the internal dissipation, the incoming field gets perfectly absorbed with no energy being back-reflected from the resonator. However, this interferometric enhancement of absorption places severe restrictions on the properties of the incoming field. For example, in the case of a single incoming channel (mode), the optical frequency needs to be precisely tuned to a resonator’s critically coupled resonance frequency. Generalizing the critical coupling condition to multichannel scattering problems leads to the phenomenon of coherent perfect absorption, for which the incoming wavefront in all available scattering channels needs to be adjusted, in addition to the spectral tuning. In other words, whether it is two laser beams impinging on an absorbing structure or a complex microwave field hitting a disordered arrangement of obstacles, at the critical coupling condition, only a single, suitably adjusted wavefront gets coherently perfectly absorbed. Although this required wavefront adjustment opens up the possibility of controlling the absorption process interferometrically, it also comes with the limitation that, apart from the correctly matched input wavefront, all of the possibly many other modes are only weakly absorbed because of the different interference patterns that they create. To overcome this restriction, recent works have managed to merge two perfectly absorbed modes at a so-called exceptional point, resulting in chiral absorption.

Here, we demonstrate how to remove the limitation of the number of perfectly absorbed modes in a coherent perfect absorber (CPA) entirely. Our design principle for a corresponding multimode CPA is based on the insight that coherent perfect absorption formally corresponds to the time-reverse of laser emission at the first lasing threshold. To create a device that can perfectly absorb arbitrary combinations of incoming modes interferometrically, one is thus required to time-reverse a laser that emits all of these modes in parallel. Such a laser is known as a degenerate cavity laser and is based on a cavity that self-images the field on either one of the two outer cavity mirrors onto itself after each cavity round trip. This can be realized in a straightforward fashion by placing two lenses in an imaging telescope configuration inside the cavity, ensuring coherent perfect absorption of any combination of modes regardless of their relative phases.

We illustrate the concept of a massively degenerate CPA (MAD-CPA) side by side with a conventional single-mode CPA (Fig. 1). The simplest conventional CPA is engineered to absorb a plane-wave input at normal incidence by placing a critically coupled absorber between two plane mirrors. For such an input, all reflections from the multiple cavity round trips converge in phase, so that the original wave is indistinguishable from the input plane wave. However, the proposed MAD-CPA can perfectly absorb any complex incident wavefront. This is achieved by placing the weak absorber in a degenerate (self-imaging) cavity, realized here by a cavity with two lenses in a telescopic arrangement. In such a degenerate cavity, all reflections from the multiple cavity round trips show perfect destructive interference with the outer reflection from the front cavity mirror, \( R_1 \), (depicted for two incoming beams at different angles).

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trips overlap and destructively interfere when the CPA condition is met. The total reflection is reduced to zero and all of the energy is absorbed. However, for any other input field that is incident at a different angle or in another mode, the reflected fields from the multiple round trips do not have a spatially identical distribution anymore; their destructive interference is out of sync and perfect absorption cannot be achieved (Fig. 1A). To realize a CPA that can universally absorb any arbitrary, complex spatial mode, one must ensure that all of the resonant cavity reflections coincide and destructively interfere with the nonresonant reflection at the front cavity mirror. This condition is naturally fulfilled in a degenerate (self-imaging) cavity design (Fig. 1B), which forms the basis for the degenerate cavity lasers that have been studied extensively for their unique lasing properties (18–20). Self-imaging is maintained for any mode supported by the cavity optics, be it a plane wave at any angle or a highly complex field with a complicated wavefront or even spatially incoherent fields.

In our experiment, we used a degenerate linear cavity composed of a lens-based telescope placed inside a cavity having a total length of \(4 - f\) (Fig. 2A), with \(f\) being the focal length of each lens (21). This resonant cavity featured a partially reflecting mirror at the front (with a reflectivity of \(R_1 = 70\%\)) and a nearly perfectly reflecting mirror at the back (with \(R_2 = 99.90\%\)). A weakly absorbing 0.6-mm-thick color-glass absorber with a single-pass transmission of \(T_{\text{abs}} = 85.2\%\) was placed next to the front cavity mirror. The CPA conditions were met simultaneously for all input modes (even for the relatively thick absorber; see supplementary text S3.1) when the cavity length was resonant with the laser wavelength. The coherent nature of absorption in the MAD-CPA allowed rapid control, including strong suppression of the absorption to values well below the absorber’s bare absorption value, by simply tuning the cavity length by a fraction of a wavelength. We characterized the degenerate CPA by injecting complex input fields using a spatial light modulator (SLM) illuminated by a wavelength-stabilized helium–neon laser. For each injected complex field, we measured the spatial distribution of the reflected light by imaging the front cavity mirror on an sCMOS camera. The very weak light intensity transmitted through the back cavity mirror was also measured for validation purposes (Fig. S4).
With the MAD-CPA being the equivalent of a time-reversed degenerate laser at threshold, the conditions necessary for reaching degenerate CPA are the same as the threshold lasing conditions. First, in lasing, the round-trip power gain, \( G \), should be equal to the round-trip losses, i.e., \( R_2 G = 1 \) (assuming \( R_2 = 1 \)). In a CPA, this condition translates to the critical coupling condition \( (3) \): \( R \left( T_{\text{abs}}^2 \right)^{-1} = 1 \). Second, the cavity must be aligned for perfect self-imaging after one round-trip propagation. Third, the cavity length must be resonant with the input wavelength. As detailed in supplementary text S3, these conditions were met in our experiments by selecting a front cavity-mirror reflectivity that matched the absorption of the cavity absorber, carefully aligning the cavity optics, and tuning the cavity length to resonant maximal absorption (Fig. 2, C to E).

To illustrate the versatility of our MAD-CPA setup, we injected into it a highly complex input field, in which >1000 modes coherently formed a speckled yin-yang symbol. Figure 2, B to E, presents the corresponding experimental results for the back-reflected light field while tuning the cavity length. As a hallmark of the successful operation of our device, we observed that the reflected power of all the input modes in the yin-yang input field was simultaneously minimized when the cavity length was tuned to meet the CPA condition (Fig. 2, C and E, and movie S1).

The minimal experimental value reached for the reflectivity was \( \approx 5\% \), indicating that the weak 15\% absorption of the intracavity absorber now featured >94\% absorption for all incoming modes simultaneously. Moreover, each spatially localized mode (speckle) of the complex field was nearly perfectly absorbed, reaching a reflected power of \( \leq 2\% \) (Fig. 2, C and D, insets). When the cavity length was tuned by \( \lambda/4 \) away from perfect absorption condition, absorption was interferometrically suppressed to values well below the incoherent single-pass transmission of the absorber, providing a modulation depth of \( >50 \) for each spatially localized mode.

The small experimental deviations from perfect absorption were mainly the result of weak spurious reflections from the cavity lenses’ antireflection coatings \( (R = 0.13\% \text{ per surface;} \text{fig. S3}) \) and by the very small aberrations (<\( \lambda/100 \)) of the self-imaging cavity optics and alignment, which led to slightly different cavity round-trip lengths for the different modes (Fig. 2C, Inset, and fig. S1). Our numerical study showed that the small mismatch in the absorption value of the cavity absorber from the critical coupling condition was not a dominant source of deviation from perfect absorption (fig. S2C), such that a commercially available absorber and a suitable front cavity mirror can be used. The influence of such experimental imperfections is discussed and analyzed numerically in supplementary text S2, showing very good agreement with the experimental measurements (Fig. 2D).

To further demonstrate the flexibility inherent in the MAD-CPA design, we illustrated its ability to absorb dynamic, rapidly changing complex random light fields that were naturally generated by transmission through flexible multimode fibers (MMFs) and dynamic atmospheric aberrations (Fig. 3). We achieved this by replacing the SLM with a 40-cm-long MMF (21). The coherent light propagation through the MMF generated complex speckle fields caused by the dispersion of the fiber
modes (Fig. 3C). To generate not only such a spatial complexity but also complex temporal dynamics, we rapidly shook the MMF using an external airflow. Moreover, before injecting the speckle fields into the cavity, we let them propagate through dynamic atmospheric aberrations generated by a hot air stream from a heat gun (Fig. 3A). The results of these experiments are shown in Fig. 3 for different variations dynamics. In all cases, similar near-perfect absorption values were achieved at CPA conditions (Fig. 3B), even for temporal variations that were faster than the camera exposure time, representing the absorption of spatially incoherent light fields, the time-reversed version of spatially incoherent lasing (19). Absorption will remain unchanged as long as the bandwidth of the input fields is narrower than the cavity absorption linewidth. This enables perfect absorption of dynamically varying fields as long as the correlation time, $\tau_{\text{corr}}$, of the temporal dynamics is longer than the photon-decay time in the cavity. Figure 3C displays individual camera frames from these dynamic absorption experiments (see also movies S2 to S5).

The number of modes that can be supported by the MAD-CPA is limited by the space-bandwidth product of the self-imaging optics (19). Perfect absorption occurs as long as the incoming wavefronts are within the angular acceptance and the imaged area of the self-imaging cavity optics (19) and their spectral bandwidth is within the spectral linewidth of the degenerate cavity (supplementary text S3.2).

It may be interesting to explore whether perfect absorption can also be useful for enhancing the sensitivity in multipass microscopy (22, 23) and if other degenerate cavity designs, such as those making use of a smaller number of optical elements, may offer practical advantages (15). The ability of a MAD-CPA to enhance or suppress absorption with high contrast for thousands of modes simultaneously also offers the interesting potential for optical modulation and switching, particularly when the goal is to absorb a large fraction of the incidence power in a weakly absorbing sample such as a single or a few molecular layers. This flexible enhancement and suppression of absorption is hard to achieve by simple optical focusing on a given absorber.

Other promising extensions of the MAD-CPA concept include its use as a highly multimode reflectionless scattering system (24). Placing an SLM inside the laser cavity (19) may also allow one to digitally control or compensate for absorption and aberrations.

Although our work has focused on the spatial degrees of freedom of the incoming waves, it would be fascinating to achieve broadband absorption also in the spectral domain (25–27), a direction in which advances have recently been made using exceptional points and nonlinear media (11–13, 28).

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Supplementary Text

Figs. S1 to S4

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Movies S1 to S6

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