

Programmable All-Optical Spin Simulator with Artificial Gauge Fields

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The coupling of lasers plays an important role in a variety of research activities, from generating high-power lasers to investigating out-of-equilibrium coupled systems. This Letter presents our investigations of Hermitian coupling in arrays of lasers, where it is possible to control both the amplitude and phase of the coupling and generate artificial gauge fields. The Hermitian coupling is demonstrated in three laser array geometries: a square array of 100 lasers with controlled laser coupling for obtaining continuous control over the phase-locked state, a triangular array of 130 lasers with controlled chirality of the lasers, and a ring array of eight lasers with a controlled topological charge. In the square array, we implemented arbitrary laser coupling with a precision of $2\pi/120$ radians, enabling the attainment of arbitrary phase-locking states. In the triangular array, we controlled the chirality of the lasers with 99% purity. In the ring array, the introduction of an artificial gauge field revealed discrete quantized first-order transitions between distinct topological phase-locking states. The results pave the way for exploring spin systems with programmable coupling in an all-optical spin simulator.

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Spin simulators are powerful tools for investigating and understanding the interactions of many body Hamiltonians in classical and quantum regimes [1–4]. Indeed, they have been recently used in a variety of areas, including ultracold atoms [5–7], quantum electrodynamics [8–11], trapped ions [12–16], and superconducting circuits [17–19]. Photonics platforms are most attractive for spin simulators as they offer accurate control, scalability, long range, dissipative and tunable coupling, room temperature operation, and advanced fabrication tools. Some have already been exploited to develop large scale and well controlled optical spin simulators that are based on coupled lasers [20–25], optical parametric oscillators [26,27], polariton Bose-Einstein condensates [28–31], and nanolasers [32,33].

Of particular importance are classical spin simulators that are much simpler to operate and control while maintaining inherent universality [34–37], special physical states [21,38], and can be mapped onto hard computational and optimization problems [3,4,28,29,39–42]. Most classical photonic spin simulators do not have a real magnetic moment, so it is necessary to synthesize artificial

gauge fields (AGFs) in order to simulate their interactions with external magnetic fields. With such AGFs it is possible to control reciprocity, topological states, vorticity, flux quantization, fractional charges, and additional exotic physical effects [43–48]. Topological investigations with coupled optical oscillators show that the AGFs correspond to Hermitian coupling between pairs of oscillators n and m . Specifically, the coupling between oscillators satisfies $K_{mn} = K_{nm}^*$ [44,49].

Some AGFs were implemented with coupled nanophotonic cavities and oscillators where optical reciprocity was broken by the non-Hermitian internal structure of individual oscillators and complex coupling was provided by waveguides with controlled lengths [48,50,51]. But in these, the connectivity is limited due to in-plane geometry, alignment is sensitive, and control of the coupling is limited. Other AGFs as well as topological lasing were implemented in pioneering works with time-multiplexed photonic resonator networks in a long optical fiber system with tunable couplings [52,53]. But these are not suitable for spin simulators.

In this Letter, we present a method for designing and generating AGFs in an all-optical XY spin simulator that allows for many controllable parameters and rapid reaction times. It is based on arrays of coupled lasers with dissipative coupling, which are formed in a digital degenerate ring cavity laser where the minimal-loss lasing state can be mapped onto the ground state of an effective spin Hamiltonian [20,21,54–57]. For a detailed treatment of the mapping condition above lasing threshold and for frustrated geometries see Ref. [54]. We developed a new arrangement where we incorporate Hermitian coupling

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so that the XY spin Hamiltonian for coupled lasers of equal intensities is

$$H_{XY} = - \sum_{mn \text{ NN}} |K_{mn}| \cos(\theta_n - \theta_m + \beta_{mn}), \quad (1)$$

where θ_n and θ_m are the phases of nearest-neighbor (NN) lasers n and m that correspond to two-dimensional spin angles, and $\beta_{mn} = -\beta_{nm}$ is the phase of the coupling K_{mn} (see details in Sec. I of Supplemental Material (SM) [58]). Consequently, $K_{mn} > 0$ corresponds to ferromagnetic ordering of the spins and $K_{mn} < 0$ corresponds to anti-ferromagnetic ordering. Equation (1) corresponds to an XY Hamiltonian with an AGF potential $\vec{A}(r)$ that relates to the Hermitian coupling phases β_{mn} by [44]

$$\beta_{mn} \propto \int_{r_m}^{r_n} \vec{A}(r) \cdot d\vec{l}, \quad (2)$$

where r_n and r_m are the positions of lasers n and m and the integration is done along an arbitrary path $d\vec{l}$.

We experimentally demonstrate the validity and efficacy of our method for designing and generating an AGF in our spin simulator with three different laser array geometries: a square array of about 100 lasers where we control the coupling in two dimensions, a triangular array of about 130 lasers where we control the chirality, and a ring array of eight lasers where we control the topological charge. In the square array, the phase of the coupling between NN lasers is dynamically scanned with a precision of $2\pi/120$ radians. In the triangular array, the symmetry between staggered vortex and staggered antivortex states is broken to obtain tunable chirality reaching 99% purity. In the ring array, the AGF flux is scanned to observe discrete quantized plateaus connected by sharp transitions that are caused by the periodic boundary conditions of the ring geometry.

Our experimental arrangement for implementing tunable Hermitian coupling between NN lasers in large laser arrays and generating an AGF involves a digital degenerate ring cavity laser, schematically shown in Fig. 1 (see detailed arrangement in Fig. S2 of SM [58]). The light propagates unidirectionally (by resorting to an intracavity optical isolator, not shown) and is self-imaged after every round trip by the two 4f intracavity telescopes. A first binary aperture mask located at the near-field plane defines an array of near-Gaussian lasers with a desired geometry, e.g., square, triangular, or ring arrays (insets show near-field and corresponding far-field intensity distributions). A second aperture mask, located at the mid-field plane, a distance $Z \sim Z_{\text{Talbot}}/2 = a^2/\lambda$ away from the near-field plane (with array spacing a and lasing wavelength $\lambda = 1064$ nm) provides the Hermitian coupling between NN lasers. In this novel experimental arrangement, the mid-field mask of an array of apertures was implemented with an intracavity programmable spatial light modulator where the apertures

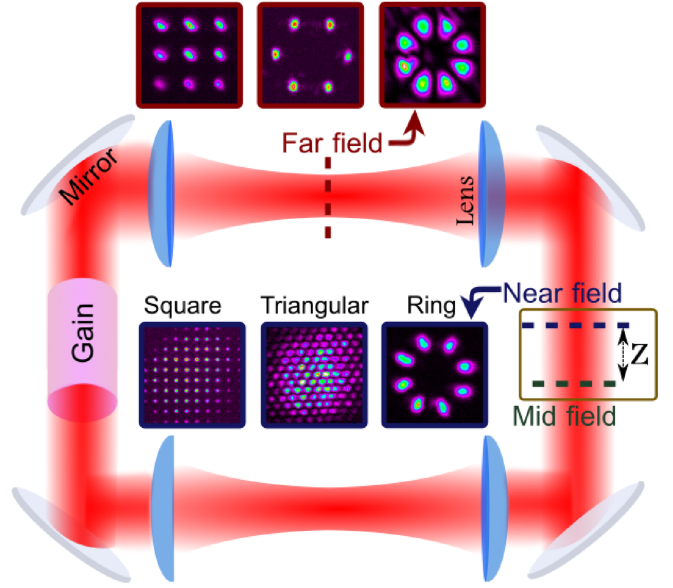


FIG. 1. Digital degenerate ring cavity laser arrangement for implementing Hermitian coupling between NN lasers and generating an AGF. An intracavity near-field aperture mask defines the laser array geometry and a second aperture mask located a distance $Z \sim Z_{\text{Talbot}}/2$ from the near-field mask, provides Hermitian coupling between NN lasers. Insets: experimental near-field intensity distributions of square, triangular, and ring laser arrays and corresponding far-field intensity distributions. The phase-locking state of the lasers can be measured from the far field. The relative positions of the near field and mid field in the box on the right are elaborated in Fig. 2.

of the mask are digitally translated and rotated so as to obtain precise control of the coupling and alignment.

To understand the basic principle of our method, consider a 1D linear array of Gaussian-mode lasers with equal spacing a between adjacent lasers (the “near field” in Fig. 2(a)). After propagating a distance Z , the field distribution of each laser expands so as to overlap the NN laser fields. A phase difference β between NN laser fields ($-\pi < \beta < \pi$) results in destructive interference, forming dark fringes at “mid-field” transverse positions $X_\beta = a(\beta/2\pi)$, at $Z = Z_{\text{Talbot}}/2$ (“mid-field” in Fig. 2(a)). Placing an absorptive mask at each of these positions, with the highest absorption at X_β , ensures a minimal loss for a phase difference β between NN lasers. With such a mid-field absorptive mask, mode competition ensures that the minimal-loss lasing solution has a phase-locked difference β between NN, corresponding to Hermitian coupling between NN, i.e., $K_{n,n+1} = \kappa e^{i\beta}$ and $K_{n+1,n} = \kappa e^{-i\beta}$. See analytic proof for Hermitian coupling in an arbitrary geometry in Sec. VII of SM [58].

We numerically calculated the coupling $K_{n,n+1} = \kappa e^{i\beta_{n,n+1}}$ between NN lasers when using a binary mid-field absorption mask of apertures with a fill factor of 0.09, while X_β was varied from $-a/2$ to $a/2$. The results are presented

in Fig. 2(b). As evident, the coupling strength is nearly constant while the coupling phase $\beta_{n,n+1} = -\beta_{n+1,n}$ is exactly $2\pi(X_\beta/a)$, as expected for the minimal-loss lasing state. Increasing the fill factor of the mask and/or the distance Z increases the coupling strength between NN lasers but also increases the effects of next nearest-neighbor

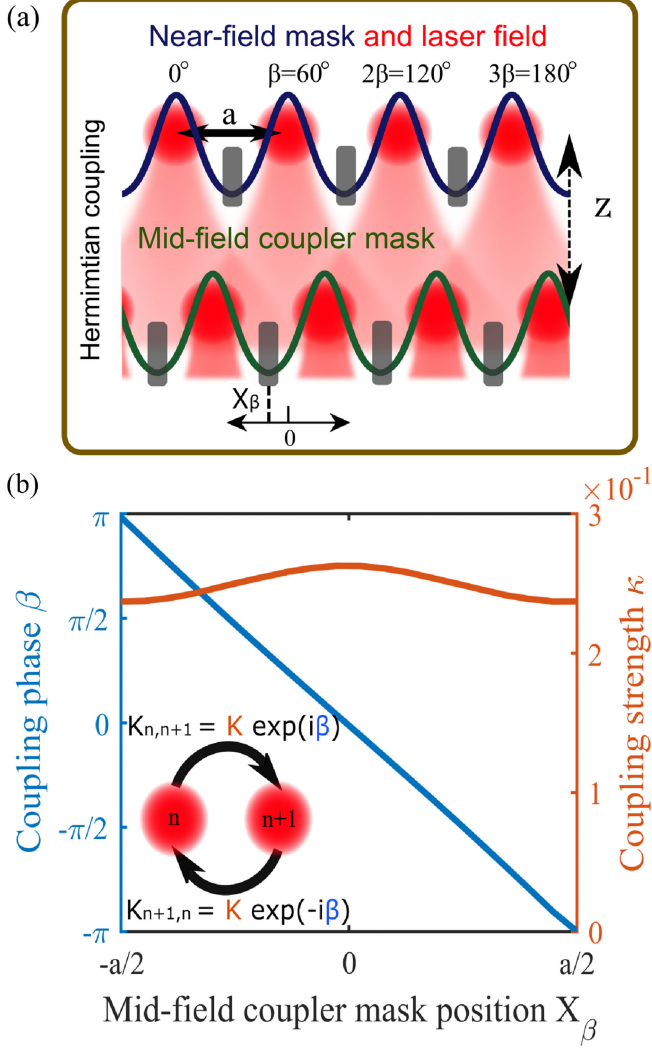


FIG. 2. Phase controlled coupling of lasers by an intracavity mid-field mask of an array of apertures. (a) Top: an intracavity near-field mask defines a linear array of four Gaussian lasers with separation a . Bottom: the mid-field mask of an array of apertures with absorptive parts, located $Z_{\text{Talbot}}/2$ away from the near-field mask. The mask is shifted laterally by $X_\beta = a(\beta/2\pi)$ so the absorptive parts overlap the dark fringes at the mid-field plane, thereby ensuring a minimal-loss lasing state. Here, the phase difference β between lasers was chosen as $\beta = 60^\circ$. (b) Numerically calculated coupling $Ke^{\pm i\beta}$ as a function of the mid-field mask position. The coupling strength (upper Gaussian curve) is symmetrical around the zero position of the mask, i.e., $|K_{n,n+1}| = |K_{n+1,n}|$, while the coupling phase (lower linear curve) is Hermitian, i.e., $\beta_{n,n+1} = -\beta_{n+1,n}$, which is in agreement with the minimal-loss picture described in (a).

coupling (see Fig. S1 of SM [58]). Such minimal-loss phase-locking method also applies to two-dimensional laser arrays where the Hermitian coupling corresponds to an AGF.

In our first experiment, we resorted to a square array of about 100 lasers (near-field intensity distribution shown in Fig. 3(a)), where we varied the position of the square array of circular apertures of the mid-field coupler mask horizontally and/or vertically to control the phase of both the horizontal and vertical Hermitian coupling between NN lasers and force the entire array to phase lock. Representative results are presented in Fig. 3. Figure 3(a) shows the experimental near-field and far-field intensity distributions at four different positions of the mid-field coupler. The sharpness of the far-field diffraction peaks indicates good phase locking, and their positions determine that the horizontal and vertical phase differences between NN lasers are $(0,0)$, $(0,\pi)$, (π,π) , and $(\pi,0)$. Figure 3(b) shows the experimental phase of the Hermitian coupling as a function of the mid-field coupler mask horizontal position X_β , indicating excellent agreement to the predicted linear relation $\beta_{n,n+1} = -\beta_{n+1,n} = 2\pi(X_\beta/a)$, with root mean square error of $\approx 2\pi/120 (= \lambda/120)$. Figure 3(c) shows the experimental phases of the Hermitian coupling when it is varied along a closed contour at the edges of a single cell in the far field of the square array, i.e., the first Brillouin zone (details in Fig. S3 of SM [58]), demonstrating the ability to obtain arbitrary horizontal and vertical phases of the Hermitian coupling between NN lasers. These results

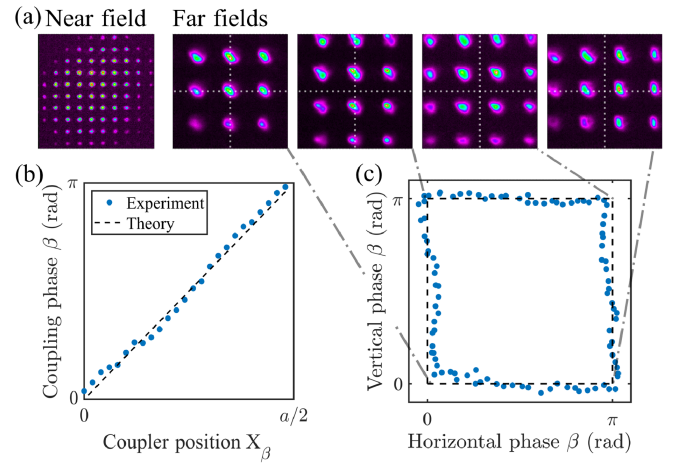


FIG. 3. Controlled phase locking of 100 lasers in a square array. (a) Experimental near-field and far-field intensity distributions of the array at four representative mid-field coupler mask positions that correspond to horizontal and vertical phase differences between NN of $(0,0)$, $(0,\pi)$, (π,π) , and $(\pi,0)$. (b) Phase β of the Hermitian coupling as a function of the coupler mask horizontal position X_β , showing excellent agreement between experiment and theory. (c) Experimental horizontal and vertical coupling phases as the mid-field coupler mask is scanned along the edges of the first Brillouin zone.

essentially demonstrate our control over the ground state of the simulated XY spin Hamiltonian.

We found that our arrangement with the mid-field coupling provides 300-fold reduction in the sensitivity to misalignment as compared to arrangements without mid-field coupling [51]. Specifically, as shown in Fig. 3(b), a lateral shift of the mid-field mask by the laser spacing $a = 300 \mu\text{m}$ changes the phase of the coupling by 2π . Such inherent robustness enables extremely accurate control of the coupling phase to a precision of $2\pi/120 (= \lambda/120)$.

In our second experiment, we resorted to a triangular array of 130 lasers (Fig. 1, center insets). We varied the Hermitian coupling between NN lasers by locally rotating a mid-field coupler mask, located at a distance $Z = Z_{\text{Talbot}}/4$ from the near-field plane. A section of the mask for three representative local rotations ($-\pi/6$, 0 , and $\pi/6$) is depicted in Figs. 4(a)–4(c), respectively. A far-field circular aperture provided additional real negative coupling between NN lasers [60].

The combination of the mid-field coupler masks and a far-field circular aperture leads to a long-range phase-locked state with a staggered chirality that is controlled by the local rotation of the mid-field coupling mask. Representative results are presented in Fig. 4. Mid-field coupler mask (a) resulted in three sharp diffraction peaks in the far-field intensity distribution (Fig. 4, left inset, A) corresponding to a pure staggered antivortex state. Mid-field coupler mask (c) resulted in three rotated far-field peaks (Fig. 4, right inset, C) corresponding to a pure staggered vortex state, and mid-field coupler mask (b) resulted in six far-field peaks (Fig. 4, middle inset, B) corresponding to their near-equal combination.

The experimental staggered chirality was thus characterized by $(P_{\text{SV}} - P_{\text{SAV}})/(P_{\text{SV}} + P_{\text{SAV}})$, where P_{SV} and P_{SAV} are the measured powers of the staggered vortex and staggered antivortex far-field peaks, respectively. The results, shown in Fig. 4 as a function of the coupler local rotation, indicate nearly pure staggered chirality (purity $> 96\%$). Negative chirality for negative coupler rotations and positive chirality for positive coupler rotations with a sharp transition between them exactly at zero coupler rotation. Similar results reaching staggered chirality purity of 99% are presented for different apertures of the mid-field mask in Fig. S4 of SM [58].

In the third experiment, we resorted to a ring array of eight lasers (near-field intensity distribution shown in Fig. 1, right inset) and an absorptive mid-field coupler mask of a ring array of eight circular apertures at a distance $Z_{\text{Talbot}}/2$. The Hermitian coupling phase β between NN lasers is controlled by rotating the mid-field coupler mask by an angle (β/N) where N is the number of lasers. We calculated the phases of all lasers by applying a Gerchberg-Saxton algorithm [59] to the experimental near-field and far-field intensity distributions (using a procedure described in Sec. V of SM [58]) to obtain reconstructed

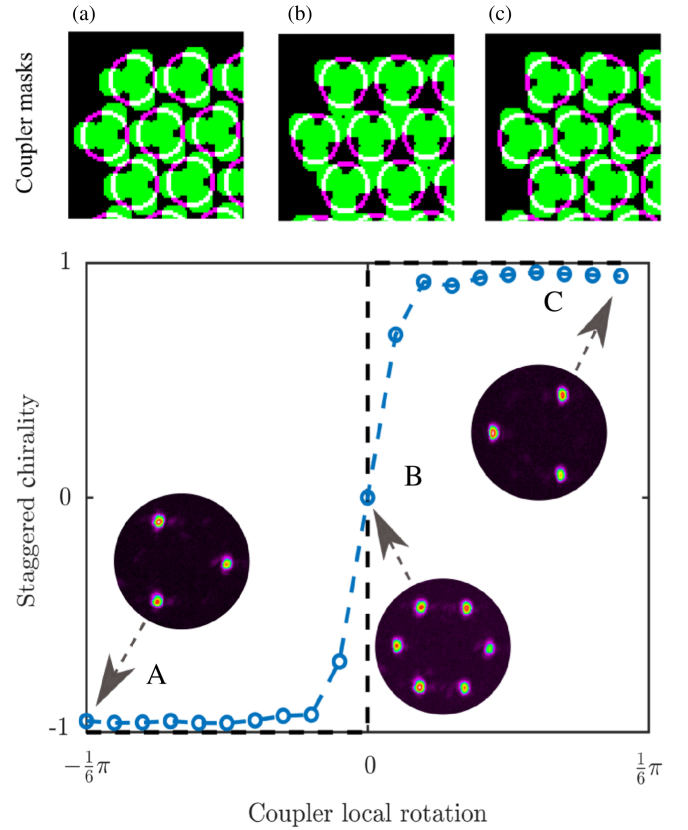


FIG. 4. Mid-field coupler mask apertures and the experimental staggered chirality as a function of the local rotation of the mid-field coupler apertures for a triangular array of 130 lasers. Black dashes: theoretical prediction for the chirality of the minimal-loss lasing state. Insets: central parts of experimental far-field intensity distributions for three local rotations of the mid-field coupler. A (left), nearly pure staggered antivortex state with negative chirality; B (center), nearly zero chirality with a superposition of antivortex and vortex states; C (right), nearly pure staggered vortex state with positive chirality. (a), (b), and (c) The shape and rotation of the mid-field coupler mask apertures (green), surrounded by absorptive areas (black), relative to the location of the near-field triangular array of lasers (pink-white circles) for local rotations A, B, and C, respectively.

laser fields at the near field composed of the experimental intensity and the calculated phase distribution. These laser fields were verified by direct interferometric measurements (see Fig. S10 of SM [58]). The ring array geometry with its periodic boundary conditions restricts the possible phase-locked states to discrete vortex solutions with integer topological charge [55,61] $Q = (1/2\pi) \sum_{n=1}^N \{\theta_{n+1} - \theta_n\}$, where $\{\}$ wraps phases in the range $[-\pi, \pi]$ and θ_n is the phase of the laser number n . $Q = 0$ or $Q = N$ correspond to the in-phase-locking state, $Q = \pm \text{int}(N/2)$ corresponds to the out-of-phase-locking state. And $2\pi \cdot Q$ is the quantized flux of the AGF through the ring.

Representative results are presented in Fig. 5. They show the experimental topological charge of the laser ring array

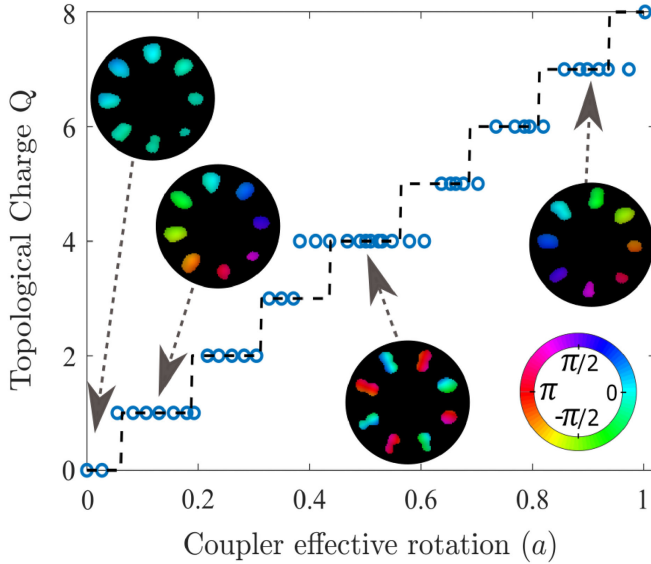


FIG. 5. Topological charge as a function of the measured effective angle of rotation of the mid-field coupler, indicating a programmable AGF in a ring of eight lasers. Black dashes: theoretical prediction for the topological charge of the minimal-loss lasing state. Insets: reconstructed laser fields (at the near field) for four representative coupler rotations corresponding to topological charges of 0, 1, 4, and 7. Brightness denotes intensity and colors denote phases.

as a function of the mid-field coupler effective rotation. The effective rotation is the measured rotation of the laser field at the mid field relative to the laser array in the near field (see details in Fig. S7 of SM [58]). As evident, there are sharp jumps between plateaus of integer values of the topological charge as the mid-field coupler angle is increased and the AGF flux reaches multiples of 2π (see insets). The experimental results agree well with the theoretical prediction for the ground state of the corresponding XY Hamiltonian with an AGF denoted by black dashes. We believe that some differences that do occur are due to the internal structure of the modes inside each laser, as observed in the reconstructed laser fields shown in the insets. Note that the experimental discrete AGF flux and topological charge in the closed ring geometry are analogous to the Harper-Hofstadter physics [44,62,63] and the integer quantum Hall effect [64].

We point out that in our experiment several factors can affect the accuracy and stability of our system's coupling control. These include spatial disorder (random phase fluctuations) [65], quenched (time-independent) disorder [66], thermal effects [67], lasers internal structures [68], and imperfections in optical components [69]. All these factors were carefully considered and mitigated in our implementation to enable $< 1\%$ accuracy of our complex Hermitian coupling.

In this Letter, we presented a method for designing and generating AGF for an all-optical spin simulator that is

based on arrays of coupled lasers, which are formed in a digital degenerate ring cavity laser with an intracavity mid-field coupler. The method involved Hermitian coupling between NN lasers with controlled and digitally programmable amplitudes and phases that resulted in a tunable AGF. We showed that it is possible to obtain accurate and robust control over the coupling phase with a remarkable 300-fold reduction in the sensitivity to misalignment as compared to systems without mid-field couplers. We experimentally demonstrated the validity of our method with three different laser array geometries, each with different features of AGF that are needed for all-optical spin simulators. They included a square array of about 100 lasers where we control coupling in two dimensions, a triangular array of about 130 lasers where we control chirality, and a ring array of eight lasers where we control the topological charge.

We believe that our method can be extended to form Hermitian coupling with nonuniform strengths or phases by resorting to nonhomogeneous mid-field masks, and even non-Hermitian arbitrary coupling with different mid-field phase masks. It may be possible to combine short-range and long-range coupling and explore unique networks, which could be of interest for quantum optical spin simulators. It will also allow one to address open questions in classical spin simulator systems that involve complex coupling, topological states, glassy phases, nonreciprocal phase transitions [70], and critical phase-locking dimension [71] and to explore the universality of the classical spin model and the unique laser dynamics in our spin simulator.

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