Non-reciprocal transmission of motion is potentially highly beneficial to a wide range of applications, ranging from wave guiding to shock and vibration damping and energy harvesting. To date, large levels of non-reciprocity have been realized using broken spatial or temporal symmetries, yet mostly in the vicinity of resonances, bandgaps or using non-linearities, thereby non-reciprocal transmission remains limited to narrow ranges of frequencies or input magnitudes and sensitive to attenuation. Here, we create a robotic mechanical metamaterials wherein we use local control loops to break reciprocity at the level of the interactions between the unit cells. We show theoretically and experimentally that first-of-their-kind spatially asymmetric standing waves at all frequencies and unidirectionally amplified propagating waves emerge. These findings realize the mechanical analogue of the non-Hermitian skin effect. They significantly advance the field of active metamaterials for non Hermitian physics and open avenues to channel mechanical energy in unprecedented ways.
Reciprocity is a fundamental property of linear, time-reversal invariant physical systems, entailing that their response functions are symmetrical, namely that signals are transmitted symmetrically between any two points in space. In other words, if one sends an electromagnetic, acoustic, or mechanical signal through a material in one direction, one can also send it in the opposite direction. While breaking reciprocity has been a long-standing challenge in electromagnetics, there has also been an explosion of interest for breaking reciprocity in optical and micro waves without magnetic fields, and beyond electromagnetism, i.e., in acoustics, quantum systems, and mechanics, thus creating new tools to engineer a novel generation of devices and materials that guide, damp, or control energy and information. Non-reciprocity has been achieved by using passive structures combining broken spatial symmetries and nonlinearities and using active time-modulated components that break time-reversal symmetry. These strategies have led to large levels of nonreciprocal isolations, but with input magnitudes or input frequencies that are limited to narrow ranges, and are sensitive to attenuation.

Here, inspired by recent developments in robotics and active metamaterials, we create a robotic mechanical metamaterial that uses distributed active control to break reciprocity at the level of the interactions between the building blocks themselves. This work builds on the field of active metamaterials, yet with a key new twist: while active metamaterials only have actuating elements, robotic metamaterials include a combination of local sensing, computation, communication, and actuation. As a result, they feature unique wave phenomena, namely asymmetric modes at all frequencies and unidirectional amplification, and in turn realize large, broadband, linear, and self-amplified nonreciprocal transmission of mechanical waves. These findings realize the classical counterpart of the so-called non-Hermitian skin effect.

**Results**

**Nonreciprocal wave equation.** We first investigate theoretically the emergent properties in a mass-and-spring model with nonreciprocal springs (Fig. 1a). For reciprocal mechanical structures, the stiffness matrix—relating displacements to forces—is symmetrical by virtue of the Maxwell–Betti reciprocity theorem. In particular, for a simple spring, left-to-right and right-to-left stiffnesses are equal: $k_{L→R} = k_{R→L} = k$ where $k_{L→R}$ and $k_{R→L}$ are defined as $k_{L→R} = F_{L→R}/(u_L - u_R)$ and $k_{R→L} = F_{R→L}/(u_L - u_R)$, where $F_L$ ($F_R$) is the force on the left (right) spring and $u_L$ ($u_R$) the displacement of the left (right) spring. Here, we consider a special mass-and-spring model, where the left-to-right and right-to-left stiffnesses differ $k_{L→R} = k(1 + \varepsilon) \neq k_{R→L} = k(1 - \varepsilon)$ (Fig. 1a). We obtain the following continuum equation (Methods, Mass-and-spring model with nonreciprocal springs):

$$\frac{1}{c^2} \frac{d^2u}{dt^2} - \frac{d^2u}{dx^2} + \frac{2\varepsilon du}{p dx} = 0,$$

where $c = p\sqrt{k/m}$ and where $p$ is the interparticle distance. In the case of reciprocal interactions ($\varepsilon = 0$), Eq. (1) becomes the wave equation, which admits dispersion-free mechanical waves of group and phase velocity $c$. For nonreciprocal interactions ($\varepsilon \neq 0$), the first-order term in Eq. (1) breaks inversion symmetry $u \rightarrow -u, x \rightarrow -x$. This asymmetry has dramatic consequences on the nature of the mechanical waves, which can be readily seen from the solutions of this equation both in the frequency domain and in real space. In the frequency domain, solutions consist of a linear combination of the functions $\exp(\pm i(\omega - q_A)x)$, where the wave vector $q_A = \frac{\varepsilon}{p} (\varepsilon \pm \sqrt{\varepsilon^2 - \omega^2 p^2 / c^2})$. For small frequencies $\omega < \varepsilon p / c$, these solutions are exponentially localized standing waves, while for large frequencies $\omega > \varepsilon p / c$, they are localized oscillatory standing waves with an exponential envelope (Fig. 1b).

Crucially, for $\varepsilon > 0$ ($\varepsilon < 0$), the imaginary part is always positive (negative), so these solutions are always localized on the right (left) edge. In real space, we obtain the Green’s function of Eq. (1) (Methods, Mass-and-spring model with nonreciprocal springs and Supplementary Information Note 1), which is an asymmetric step function propagating at a velocity $c$ with a wave front magnitude given by $\exp(\varepsilon c t / p) / 2$ and $\exp(-\varepsilon c t / p) / 2$ for $x > 0$ ($x < 0$). For any value of $\varepsilon > 0$ ($\varepsilon < 0$), the initial pulse is amplified for forward (backward) propagation and attenuated for backward (forward) propagation (Fig. 1c). This behavior can be intuitively understood from the structure of Eq. (1): work is injected in...
Nonreciprocal robotic metamaterial. In order to create a system with such effective nonreciprocal local interactions, a necessary but not sufficient condition is to add external forces. Our strategy for achieving such nonreciprocal interactions is to apply strain-dependent forces at each site, i.e., forces that are proportional to the strain in the neighboring springs. These local forces inject—linear or angular—momentum and work into the mechanical degrees of freedom. To do so, we built a metamaterial made of ten “robotic” building blocks (Fig. 2a) with rotational degrees of freedom. Each robotic unit cell consists of a mechanical rotor with a rotational moment of inertia $I$, of a local control system, and is mechanically coupled to its neighbors via pre-stretched elastic beams resulting in a torsional stiffness $C$ (Fig. 2b, c). The control system measures the rotor’s angular position $\theta$, collects that of its right neighbor $\theta_R$, and applies an additional torque on the left rotor $\tau_L = C(\alpha)(\theta_L - \theta_R)$. The parameter $\alpha$ is a dimensionless feedback parameter. The feedback gain $f(\alpha)$ plays a similar role as the parameter $e$ in the model of Fig. 1, yet with a subtle difference. In the experiment, the active force is applied only on the right neighbor, whereas in the model, the active force is applied on both left and right neighbors (Methods, Mass-and-spring model with nonreciprocal springs). We calibrate the torque vs. angle response between two unit cells and find, as expected, that $C_{L-R} \neq C$ differs from $C_{R-L} = C(1-f(\alpha))$ (Fig. 2d), therefore breaking reciprocity. While such tunable nonreciprocal response is not surprising—ultimately it is achieved at the level of each unit cell’s microcontroller—the novelty of our approach lies in coupling many such robotic nonreciprocal unit cells together and making use of the fact that the bandwidth of the electronic components is much larger than that of the mechanical degrees of freedom. As a result of the interaction between multiple robotic building blocks, unique nonreciprocal wave phenomena emerge, as we will see in the following sections.

To test the predictions of the mass-and-spring model, we now investigate experimentally and numerically the stationary response of our ten-unit cells robotic metamaterial to harmonic excitations on the left and on the right edges over a wide range of input frequencies (Methods, Calibration and measurements). In the reciprocal case $\alpha = 0$ (Fig. 3a), we observe from experiments that the amplitudes of oscillation of each unit cell either decay exponentially (low frequencies) or oscillate (high frequencies) from one unit cell to another. We model the robotic metamaterial as 10 coupled oscillators interacting with each other via nonreciprocal stiffnesses $C_{L-R}$ and $C_{R-L}$. To do so, we take into account additional effects such as the bending of the rubber bands and the inherent damping of the oscillators and quantify them via independent calibration (Methods, Numerical model of the robotic metamaterial). For all actuation frequencies, we observe from the model and the experiment that the responses to left and right excitations is simply related to mirror symmetry, which demonstrates that the metamaterial response is inherently symmetrical. In contrast, in the nonreciprocal case $\alpha = 0.43$ (Fig. 3b), we observe a strong asymmetry in the angular displacement profiles. When excited from the right, the response is more localized close to the excitation point and when excited from the left, the response is more extended toward the right and even increases for large frequencies. This asymmetry is further quantified by the spatial decays of the profiles, which are opposite in the reciprocal case $\alpha = 0$ (Fig. 3c) and differ in the nonreciprocal case $\alpha = 0.43$ (Fig. 3d), regardless of the driving frequency. Figure 3d therefore demonstrates the emergence of
transmissions as a function of the excitation frequency (f) for a feedback parameter $T$. For the nonreciprocal case, the plateau of amplitude transmission signal starkly decreases at 360 dB/decade (Fig. 3e).

For the reciprocal case, typical of a resonant low-pass filter, with a saturated plateau of amplitude $\approx 37 \pm 1$ dB at small frequencies and a broad peak corresponding to the system resonances beyond which the transmission signal starkly decreases at 360 dB/decade (Fig. 3c).

For the nonreciprocal case ($\alpha = 0.43$), the left-to-right and right-to-left transmissions differ vastly—by more than 50 dB—over a wide range of frequencies, from 0.001 to 5 Hz (Fig. 3f). Strikingly, as opposed to previous observations in mechanical metamaterials whose functionality decays with system size, such nonreciprocal isolation increases linearly with the system size (Fig. 3f—inset). Therefore, the isolation of the system can be controlled by varying the feedback $\alpha$ or by adding more unit cells, the latter having the advantage of avoiding limitations in the maximal torque applied by the control loop. Importantly, our metamaterial is linearly stable over a wide range of feedback parameters ($\alpha < 0.93$) (Methods, Numerical model of the robotic metamaterial).

Therefore, the existence of the asymmetric modes at all frequencies leads to an extremely large level of nonreciprocal transmission over a very large range of frequencies, a performance that is unprecedented among wave-based physical systems.

Since the nonreciprocal transmission is broadband, our robotic metamaterial is in principle an excellent nonreciprocal device for pulses, which have a broadband spectral signature. To demonstrate this, we excite our metamaterial with half-sine shaped pulses closely mimicking a pulse of amplitude 0.04 rad and duration 100 ms, either from the left or right edge. In the reciprocal case $\alpha = 0$, the response is strictly the same regardless of the excitation point (Fig. 4a–c).

The pulses propagate across asymmetric modes at all frequencies, as predicted by the solutions of Eq. (1) and reminiscent of the non-Hermitian skin effect. Does such strong asymmetry lead to nonreciprocal transmission?
the metamaterial, reach the opposite edge, and rapidly attenuate upon reflection. After a short transient and before the first reflection, the pulse amplitude decreases (Fig. 4c). By contrast, in the nonreciprocal case $\alpha = 0.62$ (Fig. 4d–f), the pulse attenuates strongly when excited from the right and is amplified when excited from the left. In the latter case, the pulse reaches the right edge of the robotic metamaterial and remains localized in the vicinity of this edge from where it slowly decays in time (see Supplementary Fig. 7). To quantify the pulse attenuation, we restrict our attention to the propagation before the first reflection (Fig. 4c, f). We find that the unidirectional amplification is controlled by the level of feedback $\alpha$: the signal is amplified (attenuated) for $\alpha > 0.5$ ($\alpha < 0.5$) (see Fig. 4f—inset). These observations are in qualitative agreement with the behavior of the Green’s function of Eq. (1) discussed above.

**Discussion**

To conclude, we have created a class of robotic mechanical metamaterials that are embedded with nonreciprocal interactions through local control loops. As a result, they feature a unique type of wave phenomena, which show spatial asymmetry of standing waves at all frequencies, leading to an unprecedented broadband giant level of non-reciprocity, and which exhibit unidirectional amplification of pulses. As opposed to existing metamaterials by using nonlinearities or active components, where the non-reciprocal effects tend to be suppressed by attenuation for large system sizes\(^3\), the key new feature here is that nonreciprocal waves are unidirectionally amplified, which guarantees robustness against attenuation. Nonreciprocal robotic metamaterials could be used to extract mechanical energy, allowing energy to flow away from a source while preventing energy to flow back to it. Therefore, we envision that further developments on nonreciprocal robotic metamaterials will provide new vistas for applications where unidirectional transmission of energy is useful, e.g., for communication and sensing\(^3\), shock and vibration damping, and energy harvesting\(^1\),\(^3\),\(^7\),\(^9\),\(^20\),\(^33\),\(^34\). Our study opens up a plethora of future research directions, e.g., the investigation of odd elasticity\(^22\), instabilities\(^28\), and non-Hermitian physics\(^33\),\(^28\),\(^39\). Finally, we believe that recent
developments in stimuli-responsive materials\(^{40,41}\) and robotics—via MEMS or graphene origami\(^{39,42}\)—will allow to embed active control in materials as a smaller scale, for higher dimensions, and beyond rotational degrees of freedom—e.g., for acoustics, flexural waves, and quantum systems.

**Methods**

**Mass-and-spring model with nonreciprocal springs.** In this section, we describe the mass-and-spring model with nonreciprocal interactions discussed in Fig. 1 of the main text and derive its continuum limit (Eq. (1) of the main text). We then calculate its solutions in the frequency domain as well as its Green’s function.

Consider a mass-and-spring model, where all masses are equal and all the springs are equal and of rest-length. Newton’s second law reads

\[
m \frac{d^2 u_j}{dt^2} = F_{j-1,j} + F_{j+1,j},
\]

where \(u_j\) is the displacement of mass \(j\) and \(F_{j-1,j} = k_{j-1,j} (u_{j-1} - u_j)\) and \(F_{j+1,j} = k_{j+1,j} (u_j - u_{j+1})\) is the force exerted by the spring between masses \(j-1\) and \(j\) and \(j+1\) and \(j\). In an ordinary reciprocal system, \(k_{j-1,j} = k_{j+1,j} = k\), and the right-hand side of Eq. (2) becomes \(k (u_j - u_j - 2u_j)\). By contrast, here we consider a special case where the springs are nonreciprocal \(k_{j-1,j} = k_{j+1,j} = k (1 + \epsilon) = k_{j-1,j} = k (1 - \epsilon)\). In such a model, Newton’s action–reaction third law is broken, which means that in practice one needs to add local momentum at each site \(j\) to realize such a system. The equation of motion for mass \(j\) becomes

\[
m \frac{d^2 u_j}{dt^2} + k (1 + \epsilon) (u_j - u_{j-1}) + k (1 - \epsilon) (u_j - u_{j+1}) = 0.
\]

In order to study the behavior of such a system, it is useful to consider the continuum limit, given by \(u_j \rightarrow u(x)\) and \(u_{j+1} \rightarrow u(x+\epsilon)\). In this case, the resulting system \((\epsilon = 0)\) becomes the wave equation, which admits dispersion-free mechanical waves of group and phase velocity \(c\). For arbitrary \(\epsilon \neq 0\), Eq. (1) is analogous to the Telegrapher’s equation\(^{53,44}\), where time and space have been interchanged.

If we assume that the medium is infinite, the Floquet–Bloch theorem predicts that plane wave solutions of the form \(u(x,t) = u_0 \exp(\omega t - q x)\) are solutions of Eq. (1), where \(\omega\) is the radial frequency and \(q\) the wave vector. By inserting this expression in Eq. (1), we obtain the following dispersion relation

\[
\omega^2 = \frac{k}{m} + \frac{2\epsilon \omega}{p} = q^2.
\]

Therefore, for a given \(\omega\), solutions are of the form \(u(x,t) = \exp(\omega t - q x)\), where \(q = \sqrt{\omega^2 - \frac{2\epsilon \omega}{p}}\). This result is discussed in the main text.

We calculate the Green’s function of Eq. (1) by using Fourier–Laplace transforms (see Supplementary Note 1) and find

\[
u(x,t) = \frac{\omega^p}{2p} \cdot \frac{\exp(-\frac{\omega t}{p})}{\omega^p} \cdot \begin{cases} \frac{\sqrt{\omega^2 - \frac{2\epsilon \omega}{p}}}{\omega^p} & \text{for } \omega > 0 \\ \frac{\sqrt{\frac{2\epsilon \omega}{p} - \frac{\omega^2}{p}}}{\omega^p} & \text{for } \omega < 0 \end{cases}
\]

for \(\Theta = 1\). The basic algorithm of the software is depicted in Fig. 2c of the main text and runs continuously at a rate of 100 Hz. Each microcontroller collects the angular sensor measures the position of the oscillator with a precision of 14000 PPR (pulse per revolution), which translates into a precision of 4.22\(^{\circ}\) per rad.

**Microcontroller:** The microcontroller digitizes the encoder’s signal with an angular resolution of \(4 \times 10^{-10}\) rad at a rate of 100 Hz and collects the angular position of the unit cell’s right neighbor through a serial protocol (UART connection) at a rate of 100 Hz. From a 9-bit timer, the microcontroller also builds up a pulse-width modulation (PWM) signal, to control the motor. The microcontroller is integrated to a custom-made electronic board that ensures power conversion and wiring to the motor, encoder, and the neighboring unit cells. The firmware of the microcontroller is uploaded from an external computer by serial communication (USB port). Although the microcontroller is not required to be connected to an external computer to function, if required, data can also be sent to an external computer (rate 100 Hz) via the same serial communication.

**DC motor:** In order to apply a given torque, the motor is controlled by a PWM signal. The PWM signal is sent to the motor and controls the generated torque with a resolution of 0.008 mNm, up to a maximum torque of \(3.92\) mNm. Note that this equation explains the saturation of the effective stiffness \(C_{\text{eff}}\) for large values of the feedback parameter in Fig. 2d in the main text.

**Software:** The basic algorithm of the software is depicted in Fig. 2c of the main text and runs continuously at a rate of 100 Hz. Each microcontroller collects the instantaneous angular position measures of its own angular sensor \(\theta_i\) as well as the instantaneous angular position \(\theta_i\) of the right neighbor. From those two signals, the microcontroller is programmed to output a PWM signal proportional to \(g(\theta_i - \theta_{i-1})\), where the constant \(g\) is a tunable gain parameter. This signal drives the DC motor, which leads to a torque proportional to \(g(\theta_i - \theta_{i-1})\), see below for calibration.

**Calibration and measurements.** In order to perform measurements, the robotic metamaterial is actuated by a servomotor (Hitec D930DW, see Supplementary Fig. 5) controlled via a microcontroller (Arduino Mega 2560), interfaced to an external computer. The servomotor can be attached on either side of the setup and is mechanically connected to one oscillatory via two green elastic elements in rectangular shape, 6-mm thick, Elite double 32, Young’s modulus \(E = 1\) MPa, resulting in a torsional stiffness \(27.4\) mNm/rad, see Supplementary Fig. 4). These two elastic beams are sufficiently soft to ensure free rotations of the servomotor and negligible friction.

The stiffness measurements shown in Fig. 2d of the main text have been performed on two building blocks. The configuration of the setup is sketched in Supplementary Fig. 4a (see also Supplementary Fig. 5a). The left (right) oscillator was attached to a load cell (Instron 2300-5 N, resolution of 0.005 N, sampling frequency of 500 Hz) at a fixed position \(\theta_i = 0\) (\(\theta_{i-1} = 0\)), allowing us to measure the torque, \(T\), and \(\theta_i\) through the oscilloscope and the encoder, by imposing an oscillatory angular displacement \(\theta_i\) at the frequency 0.1 Hz and amplitude 0.13 rad.
As shown in Supplementary Fig. 5a–c, at small angles, the torque varies linearly with the angular position \( r_{\text{tilt}} = C \theta_{L} - \theta_{R} \), and \( r_{\text{tilt}} = C \theta_{L} - \theta_{R} \). Note that this is also verified for angles up to 3.5° rad (not shown here). We therefore perform a linear fit to the torque-angle curves to extract the values of \( C_{\text{L}} \) and \( C_{\text{R}} \). In the case \( \theta = 0 \), we find \( C_{\text{L}} = 0 = C_{\text{R}} = 22.4 \pm 0.4 \) mN m rad (Supplementary Fig. 5c). For \( \theta > 0 \), we find \( C_{\text{L}} < 0 < C_{\text{R}} \) (Supplementary Fig. 5c). By using the same protocol at different excitation frequencies, we verified that the stiffness \( C_{\text{L}} \) and \( C_{\text{R}} \) are different for \( \alpha = 0 \) for any actuation frequency (see Supplementary Fig. 5d). Note that internal vibrations start to occur at 3 Hz, which we suspect are responsible for the decrease of the measured stiffnesses as the frequency increases.

Since our calibration experiments combine symmetric and antisymmetric deformations, \( C_{\text{L}} \) is related to the stiffnesses \( C \) and \( C^\prime \) defined as \( C_{\text{L}} = C - C^\prime \). Similarly, \( C_{\text{R}} = C_{\text{L}} - C^\prime \) and \( C_{\text{L}} = C_{\text{R}} - C^\prime \). We calibrated \( C \) independently by using a slightly different experimental configuration. To do this, we connected rigidly the two oscillators such that they were moving with the same angle \( \theta_{L} = \theta_{R} \) and measured the force applied on both oscillators (see Supplementary Fig. 4b). We obtained a torsional stiffness \( C = 1.71 \pm 0.04 \) mN m rad, and as a result, \( C = 24.1 \pm 0.4 \) mN m rad as well as \( C_{\text{L}} \) and \( C_{\text{L}} \) shown in Fig. 2d of the main text.

Finally, we calibrated the DC motor by fixing the position of the right oscillator \( \theta_{R} = 0 \) and measuring the torque \( r_{\text{tilt}} \) exerted by the DC motor in the absence of the elastic beams as a function of the position of the right oscillator \( \theta_{R} \) (see Supplementary Fig. 4c). As expected, we find that \( r_{\text{tilt}} \) vs. \( \theta_{R} \) is a linear negative slope (not shown here), and by using a linear fit, we determine the gain function \( K \) as a function of the feedback parameter \( g \) controlling the amplitude of the PWM signal. For convenience, we rewrite \( K \) as \( C \) (a), where \( C \) is a dimensionless feedback parameter and \( g \) is a dimensionless gain function. We observe that \( K \) is linear in the region \( g < 1 \) and saturates for larger \( g \) (see Fig. 2d and main text).

During experiments, the robotic metamaterial was mechanically excited at different frequencies by using the servomotor. In order to remain within the resolution limit of the angular encoder, yet to remain in the linear regime, we used an excitation amplitude of 0.21 rad (0.11) for frequencies below (above) 3 Hz. In the specific case of left excitations of the nonreciprocal metamaterial, given the amplification of the signal, we used smaller excitation amplitudes of 0.04 rad. As a result, the oscillation amplitude was always between 4 × 10^{-4} and 0.25 rad, well in the linear regime. During experiments, we recorded the instantaneous angular positions \( \theta_{L} \) and \( \theta_{R} \) of each oscillator \( j \) at a rate of 100 Hz.

The amplitude of oscillation \( \theta_{j} \) of each time series \( \theta_{j} \) was extracted from these measurements by performing a Fourier series analysis on the signal collected from the microcontroller \( \theta = \sqrt{\theta^2 + \theta^2} \). The parameters \( a_{j} \) and \( b_{j} \) are the first coefficients of the Fourier series \( a_{j} = \frac{1}{2} \int_{0}^{2\pi} \theta(t) \cos(\omega t) dt \) and \( b_{j} = \frac{1}{2} \int_{0}^{2\pi} \theta(t) \sin(\omega t) dt \), with \( P \) the period of the impinging signal and \( \tau_{i} \) the initial time for the integration. Each experiment was performed over a minimum of 10 periods for signals above 10^{-2} Hz and 5 periods for signals below 10^{-2} Hz.

The time \( \tau_{i} \) was carefully chosen such that the oscillations were still stationary. The amplitudes of oscillation as a function of the unit cell position are shown in Supplementary Fig. 4c. As expected, we verified that the stiffnesses \( C_{\text{L}} \) and \( C_{\text{R}} \) are different for \( \alpha = 0 \) for any actuation frequency (see Supplementary Fig. 5c). By using the same protocol at different excitation frequencies, we verified that the stiffnesses \( C_{\text{L}} \) and \( C_{\text{R}} \) are different for \( \alpha = 0 \) for any actuation frequency (see Supplementary Fig. 5d). Note that internal vibrations start to occur at 3 Hz, which we suspect are responsible for the decrease of the measured stiffnesses as the frequency increases.

To solve for the dynamics upon excitations from the left (right) edge, we impose the angular displacement of the leftmost (rightmost) oscillator \( \theta_{L} \) (\( \theta_{R} \)). The numerical data plotted in Figs. 3 and 4 of the main text correspond to the numerical solution of Eq. (8) by using the values of \( C = 24.1 \) mN m rad, \( C = 1.71 \) mN rad and \( \theta_{L} \) shown in Fig. 2c of the main text.

Received: 8 June 2019; Accepted: 13 September 2019; Published online: 10 October 2019

**References**


**Data availability**

The source data underlying Figs. 1–4 are provided as source data files. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon request.

**Code availability**

The codes that support the plots within this paper and other findings of this study are available from the corresponding author upon request.


Acknowledgements
We thank D. Giesen, G. HARDeman, U. van Hes, T. Walstra, and T. Weijers for their skilful technical assistance. We are grateful to A. Alù, Y. Hadad, and J. van Wezel for their insightful discussions. C.C. acknowledges funding from the Netherlands Organisatie for Scientific Research (NWO) VENI grant No. NWO-680-47-445.

Author contributions
M.B., E.L., and C.C. designed the research. M.B. and X.L. conducted the experiments and performed the data analysis, and M. B., E.L., and C.C contributed to the theoretical model. M.B. and C.C. wrote the paper with input from E.L.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41467-019-12599-3.

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Peer review information *Nature Communications* thanks the anonymous reviewers for their contribution to the peer review of this work. Peer reviewer reports are available.

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