# switching of the NIR solar gain, while maintaining high

Controlling solar gain is essential to reduce the energy consumption by residential and commercial buildings, which are responsible for % of all energy generated globally. However, the dynamic control of solar gain in the near-infrared that corresponds to % of the overall Sun's energy at the Earth's surface, separately from the visible spectral range has been a challenge, albeit commercial coatings provide passive control while retaining highly visible transmission. To address this problem, in this paper switchable silver colloids (SSCs) are demonstrated, colloidal analogs of the common silver coatings used for solar gain control. When dispersed in a nematic liquid crystal, orientations of such plasmonic silver nanoplates are controlled by V low-voltage electric elds, allowing for sub-second switching of the near-infrared-based solar gain. Installed and retro t products made from thin lms of such nanoplate dispersions con ned between glass and plastic substrates, respectively, exhibit electrically controlled infrared-based solar gain while retaining high visible-range transparency, low haze, and high color rendering index. This study's ndings reveal a great potential of soft-matter systems in addressing energy-related problems.

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## . Results and Discussion

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Figure . Optical response of the SSCs in di erent spectral ranges. a) Transmittance versus wavelength plot for the composite in the IR-A range at di erent applied voltages. The transmission properties remain unchanged after at least cycles. b) Total transmittance of the composite in the visible range and the change of di used transmittance of pure CB after the addition of AgNPs, with and without voltage. A zoomed-in view of diffused transmittance plot is shown in the inset. c) Transmittance versus wavelength plot of the composite in the IR-A spectral range at di erent linear polarization angles of incident light. d) Transmittance spectra of the composite without ( V) and with applied voltage ( V) as compared to three di erent commercially available coated glass products (Cardinal glass products, with the commercial names shown in the legend). The dashed curve shows the data for a fully switched cell with a di erent set of nanoplates having an LSPR peak at nm.

Table 1

$$\mathrm{SH\text{-}C_{NIR}} = \frac{\int_{780}^{1400} T(\lambda)E(\lambda)d\lambda}{\int_{780}^{1400} E(\lambda)d\lambda}$$

$$\mathrm{VLT} = \frac{\int_{380}^{780} T(\lambda)V(\lambda)E(\lambda)d\lambda}{\int_{380}^{780} V(\lambda)E(\lambda)d\lambda}, \quad T(\lambda)$$

$E(\lambda)$ $V(\lambda)$

[illegible]

## . Conclusion

## . Experimental Section

Dispersionuof Colloidal Nanoparticles: The authors used silica-shelled silver nanoplates purchased from nanoComposix (San Diego) at mg mL⁻ mass concentration in an aqueous m sodium bicarbonate bu er. The particles were at rst washed once with deionized water and mass concentration. This as-prepared colloidal dispersion was stored in a refrigerator and used in the desired amount for experiments. In a typical experiment, µL of the nanoparticle dispersion was mixed with µL of pure -cyano- ′-pentylbiphenyl ( CB, from Chengzhi Yonghua Display Materials Co. Ltd.) at room temperature. The mixture was kept inside an oven at °C until all the methanol was fully evaporated. The resultant isotropic mixture was then sonicated in a water bath at °C for min and then quenched to the nematic phase while having been agitated mechanically. This process was then followed by centrifugation at rpm for min to separate out the aggregates formed during the LC phase transition, resulting in a uniform colloidal dispersion.

Sample Fabrication: The LC cells were prepared using glass substrates coated with transparent ITO electrodes on the inner surfaces to enable the application of electric elds. The authors used two types of ITO electrodes to design their experiments. The uniformly coated ITO thin lms covering the entire glass surfaces of con ning substrates were used to apply electric elds perpendicular to the glass substrates (for vertical alignment) and the micropatterned ITO coatings were used to apply electric elds tangential to the glass surface (for in-plane switching). To prepare, LC cells with planar surface anchoring the ITO-coated surfaces were spin-coated with wt% aqueous polyvinyl alcohol (PVA, from Sigma Aldrich) and baked at °C for h. The PVA-coated surfaces were then rubbed unidirectionally with a soft velvet cloth to de ne the direction for the director N and then glued together with UV-curable NOA- glue (Norland Products, Inc.) containing spacers (such as the µm silica spheres) to de ne the desired cell gap. For the homeotropic LC cells, the ITO-patterned surfaces of the glass plates were spin-coated with a polymer SE and baked at °C for h. Homeotropic anchoring on the ITO-coated exible PET substrates (from Thorlabs) was done by vapor phase deposition of H, H, H, H-per uorooctyltriethoxysilane under vacuum condition.[ ]

Electro-Optical characterization: For optical microscopy observations, the authors used an Olympus BX- upright polarizing optical microscope with the × air objective having a numerical aperture of . and a charge-coupled device (CCD) camera purchased from Pointgrey. For dark- eld imaging, the sample was illuminated with an oil-immersion dark- eld condenser (numerical aperture of . ), and the highly scattered light was collected with a ×, variable numerical aperture ( . – . ) oil immersion objective and imaged with another monochrome CCD camera (Spot Pursuit, Diagnostic Inc.). The extinction and transmission spectra were studied using two separate spectrometers dedicated to visible (Silver Nova, from Stellernet Inc.) and near-IR wavelengths (Dwarf Star, from Stellernet Inc.) mounted on the microscope. The broad-spectrum light was collected using Y-type optical ber with a µm core diameter. The collected light was split into two parts and coupled to the respective spectrometers. The electric switching of the composite was characterized using a data acquisition system (USB- , from National Instruments Co.) controlled by a homemade software written in LabVIEW (from National Instruments Co.), and a Si-ampli ed photodetector (PDA A , from Thorlabs Inc.). For the switching time measurements of the composites of CB and silver nanoplates, visible light lters were used to block visible light spectra and allow only the near-IR light that includes the longitudinal LSPR peak of the AgNPs. The photographs of the exible cells were taken with a D camera (from Nikon). The IR photographs were taken using a nm long-pass lter.

## Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

## Acknowledgements

The authors acknowledge the discussions and technical assistance of Ye Yuan. S.G. thanks B. Senyuk, T. Lee, J. B. Ten Hove, E. Abraham for helpful discussions, and P. B. De Melo for the help in taking the photographs. I.S. acknowledges funding from the US National Science Foundation's Division of Innovation and Partnership grant IIP- . I.S. and S.G. thank the US Department of Energy, O ce of Basic Energy Sciences, Division of Materials Sciences and Engineering, under contract DE-SC with the University of Colorado at Boulder for supporting the work.

## Con ict of Interest

The authors declare no con ict of interest.

## Data Availability Statement

The data that support the ndings of this study are available from the corresponding author upon reasonable request.

## Keywords

electro-optic switching, liquid crystals, plasmonic colloids, self-assembly, solar gain, transparent smart windows

Received: July ,
Published online:

[ ] S. Enoch, N. Bonod, Plasmonics, (Eds: S. Enoch, N. Bonod), Vol. , Springer Berlin Heidelberg, Berlin, Heidelberg .
[ ] S. I. Azzam, A. V. Kildishev, R. M. Ma, C. Z. Ning, R. Oulton, V. M. Shalaev, M. I. Stockman, J. L. Xu, X. Zhang, Light: Sci. Appl. , , .
[ ] M. A. Noginov, G. Zhu, A. M. Belgrave, R. Bakker, V. M. Shalaev, E. E. Narimanov, S. Stout, E. Herz, T. Suteewong, U. Wiesner, Nature , , .
[ ] S. Ghosh, A. Ghosh, Nat. Commun. , , .
[ ] S. Ghosh, A. Ghosh, Langmuir , , .
[ ] J. N. Anker, W. P. Hall, O. Lyandres, N. C. Shah, J. Zhao, R. P. Van Duyne, Nat. Mater. , , .
[ ] A. J. Haes, R. P. Van Duyne, J. Am. Chem. Soc. , , .
[ ] M. Kim, J. H. Lee, J. M. Nam, Adv. Sci. , , .
[ ] P. K. Jain, X. Huang, I. H. El-Sayed, M. A. El-Sayed, Acc. Chem. Res. , , .
[ ] H. A. Atwater, A. Polman, Nat. Mater. , , .
[ ] Y. H. Jang, Y. J. Jang, S. Kim, L. N. Quan, K. Chung, D. H. Kim, Chem. Rev. , , .
[ ] S. A. Maier, Plasmonics: Fundamentals and Applications, Vol. , Springer US, New York, NY .
[ ] Q. Liu, Y. Yuan, I. I. Smalyukh, Nano Lett. , , .
[ ] Y. Zhang, Q. Liu, H. Mundoor, Y. Yuan, I. I. Smalyukh, ACS Nano , , .
[ ] H. Takeda, K. Adachi, J. Am. Ceram. Soc. , , .
[ ] K. Manthiram, A. P. Alivisatos, J. Am. Chem. Soc. , , .
[ ] A. Llordés, Y. Wang, A. Fernandez-Martinez, P. Xiao, T. Lee, A. Poulain, O. Zandi, C. A. S. Cabezas, G. Henkelman, D. J. Milliron, Nat. Mater. , , .
[ ] R. Buonsanti, A. Llordes, S. Aloni, B. A. Helms, D. J. Milliron, Nano Lett. , , .
[ ] A. Llordés, G. Garcia, J. Gazquez, D. J. Milliron, Nature , , .
[ ] J. Kim, G. K. Ong, Y. Wang, G. Leblanc, T. E. Williams, T. M. Mattox, B. A. Helms, D. J. Milliron, Nano Lett. , , .

[ ] Y. Wang, E. L. Runnerstrom, D. J. Milliron, Annu. Rev. Chem. Biomol. Eng. , , .
[ ] N. DeForest, A. Shehabi, J. O'Donnell, G. Garcia, J. Greenblatt, E. S. Lee, S. Selkowitz, D. J. Milliron, Build. Environ. , .
[ ] H. K. Pulker, Coatings on Glass, Vol. , Elsevier, New York .
[ ] J. Ebisawa, E. Ando, Curr. Opin. Solid State Mater. Sci. , .
[ ] S. D. Rezaei, S. Shannigrahi, S. Ramakrishna, Sol. Energy Mater. Sol. Cells , , .
[ ] S. W. Tong, W. P. Goh, X. Huang, C. Jiang, Renewable Sustainable Energy Rev. , , .
[ ] J. Chai, J. Fan, Mater. Today Energy , .
[ ] P. Pattathil, R. Giannuzzi, M. M51 Tf 5 J7em. Biomol.

 