AFRL-AFOSR-UK-TR-2019-0040

Curved Space Photonics Inspired by General Relativity Concepts

Mordechai Segev
TECHNION ISRAEL INSTITUTE OF TECHNOLOGY

07/30/2019
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ IOE
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
28-02-2019

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
1 December 2015 - 30 November 2018

4. TITLE AND SUBTITLE
Curved Space Photonics Inspired by General Relativity Concepts

5a. CONTRACT NUMBER
FA9550-16-1-0024

5b. GRANT NUMBER
15IOE088

5c. PROGRAM ELEMENT NUMBER
61102F

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Segev, Mordechai

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Technion - Israel Institute of Technology
Technion City
Haifa 32000
Israel

8. PERFORMING ORGANIZATION REPORT NUMBER
2022021

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
EOARD
Unit 4515
APO AE 09421-4515

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR/IOE (EOARD)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-UK-TR-2019-0040

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project is aimed at creating a novel class of photonic devices with intricate design in full three dimensions. As opposed to typical nanophotonic devices that are designed and fabricated in planar settings by controlling the refractive index of the materials, we envision devices that control the properties of light just based on the principles of light propagation in curved space. The results of our studies have been published in top journals (two papers Nature Photonics, one in the Rapid Communications section of Physical Review A, and one in Physical Review X). In the first paper, we demonstrated a new class of nanophotonic structures in three dimension where the evolution of light is controlled through the space curvature of the medium. In the second paper, we showed that it is possible to observed new topological phenomena by using curved-space photonic lattices. In the third paper, we experimentally demonstrated the existence of accelerating beam in curved space. Finally, in our most recent paper that will be appearing shortly in Nature Photonics, we describe optical waveguiding by virtue of synthetic (artificial) gauge fields.

15. SUBJECT TERMS
EOARD, photonics, photonic devices, optics, waveguides, nanophotonics, general relativity, relativistic electromagnetism, photonic lattices, topological insulators

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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					19b. TELEPHONE NUMBER *(Include area code)* +44 (0)1895 616010

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Curved Space Photonics Inspired by General Relativity Concepts

PI: Mordechai (Moti) Segev
Department of Physics, Technion, Israel

Final Report

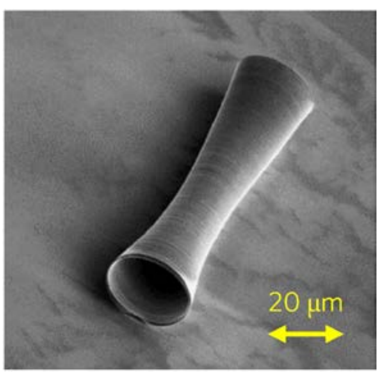
Abstract:

This project is aimed at creating a novel class of photonic devices with intricate design in full three dimensions. As opposed to typical nanophotonic devices that are designed and fabricated in planar settings by controlling the refractive index of the materials; here we envision devices that control the properties of light just based on the principles of light propagation in curved space. During the past year, we made considerable progress in this project. Two experimental and one theoretical project were finalized, and the research results are already published at top journals (two papers Nature Photonics, one in the Rapid Communications section of Physical Review A, and one in Physical Review X). In the first paper, we demonstrated a new class of nanophotonic structures in three dimension where the evolution of light is controlled through the space curvature of the medium. In the second paper, we showed that it is possible to observed new topological phenomena by using curved-space photonic lattices. In the third paper, we experimentally demonstrated the existence of accelerating beam in curved space. Finally, in our most recent paper that will be appearing shortly in Nature Photonics, we describe optical waveguiding by virtue of synthetic (artificial) gauge fields.

Below I briefly describe the main research achievement on this project.

Control of light by curved space in nanophotonic structures in Photonics

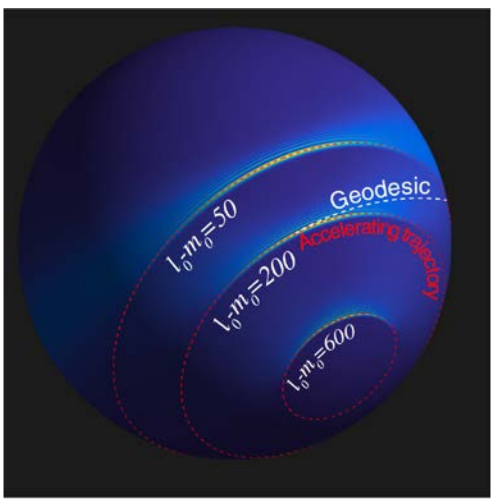
Published in Nature Photonics [1]



In this project we experimentally demonstrated a completely new paradigm for nanophotonics: Nanophotonics in 3D Curved Spaces. In general, nanophotonics is based on the ability to construct structures with specific spatial distributions of the refractive index. Conventional nanophotonic structures are fabricated in planar settings, similar to electronic integrated circuits. In this project, we first designed a new class of nanophotonic structures in full three dimensional settings where the evolution of light is controlled through the space curvature of the medium. The design was inspired by General Relativity concept. For example, we designed a paraboloid structure inspired by the Schwarzschild metric describing the space surrounding a massive black hole. After that, we fabricated such complex nanometric photonic structures by using state of the art 3D nanoprinting techniques. Finally, we experimentally demonstrated and characterized the propagation of light in these nanometric 3D photonic structures. We demonstrated that this structure allows control over the trajectories, the diffraction properties and the phase and group velocities of propagating wavepackets. In doing that, we observed a new unconventional phenomenon: our structure exhibits tunneling through an electromagnetic bottleneck by transforming guided modes into radiation modes and back. We expect that this new phenomenon can serve as the basis for curved nanophotonic devices and can be employed in integrated photonic circuits.

Observation of Accelerating Wave Packets in Curved Space

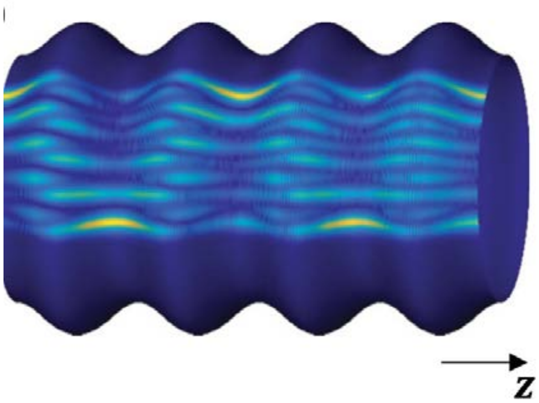
Published in PHYSICAL REVIEW X, [2]
Highlighted with a Synopsis in APS. Physics.



In recent years, researchers have shown that optical wave packets (beams) can propagate in a self-accelerating manner, where the structure of a beam is engineered to move along a curved trajectory. This field has attracted major interest, with many potential applications ranging from curved plasma channels using femtosecond Airy beams, manipulation of microparticles in nonconventional ways, and laser micromachining along a curve, to single-molecule imaging using the curved pointspread function, light-sheet microscopy using Airy beams, among many others. In this project, we took these accelerating beams one step further, demonstrating them in a medium that has a curved space geometry, where the trajectory of the accelerating beam is determined by the interplay between the curvature of space and interference effects arising from the beam's structure. First, we theoretically showed the existence of shape-preserving accelerating beams propagating on spherical surfaces: closed-form solutions of the wave equation manifesting nongeodesic self-similar evolution. After that we experimentally generated such specifically shaped beams, and coupled them into a thin hemispheric glass shell that served as the curved-space landscape for the light. We experimentally observed that the brightest lobe of this beam bends away from the shortest (geodesic) path, which is the trajectory that light would normally take on the sphere. This work is the first experimental observation of accelerating beams in curved space. We observed that unlike accelerating beams in flat space, these wave packets change their acceleration trajectory due to the interplay between interference effects and the space curvature, and they focus and defocus periodically due to the spatial curvature of the medium in which they propagate. These experiments provide new avenues for controlling trajectories of light in nonplanar 3D settings and offer new opportunities for emulating general relativity.

Curved-space topological phases in photonic lattices

Published in PHYSICAL REVIEW A, **Rapid Communication** [3]



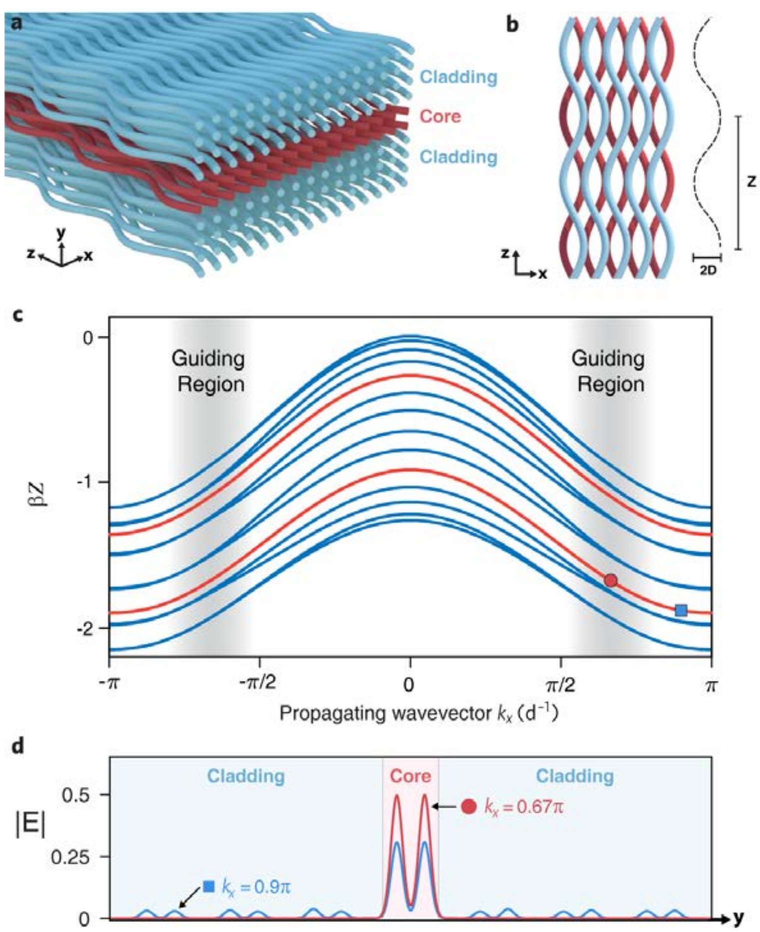
During the last decade, photonic lattices have become a very powerful platform in optics and photonics. Such, 1D or 2D arrays of waveguides have served to demonstrated new fundamental physics like Floquet photonics topological insulators, PT-symmetry, Anderson Localization, among many others. In this project, we presented a new idea on how to control the properties of photonic lattices by controlling the curvature of the embedded space. We showed that the interplay between the curvature of space and the topology of the system gives rise to a wealth of new phenomena. For example, we showed that, by engineering the curvature of space we can induce topological edge states, topological phase transitions, Thouless pumping, and localization effects. Finally, it is important to point out that all the concepts in this project are based on an experimentally viable photonic setting, a thin 2D waveguiding layer covering the surface of a three-dimensional body, where the light effectively propagates in 2D curved space.. Currently we are working on the experimental realization.

Light guiding by artificial gauge fields

To appear Nature Photonics, March 2019 [4].

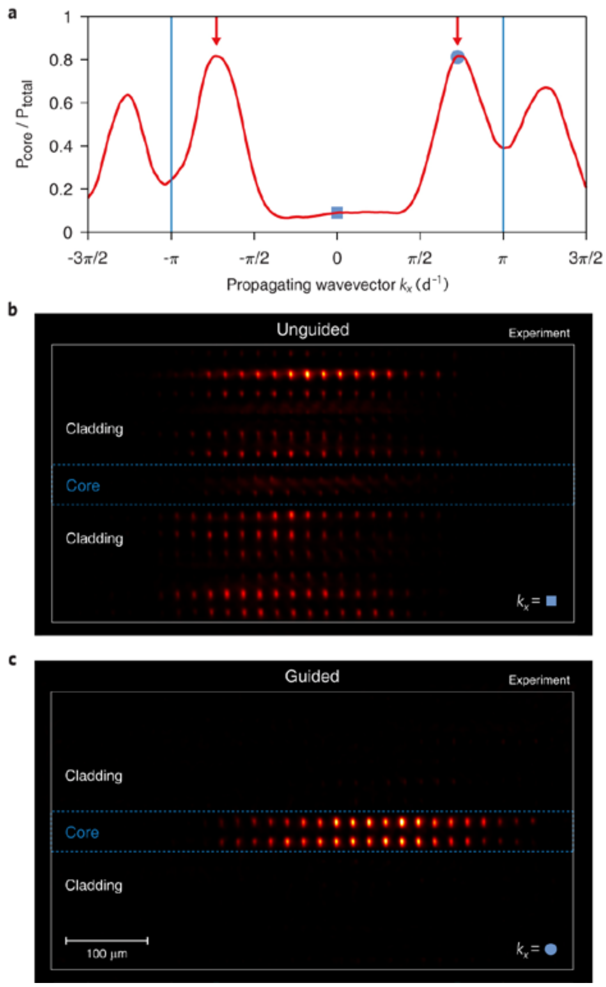
The use of artificial gauge fields enables systems of uncharged particles to behave as if affected by external fields. Generated by geometry or external modulation, artificial gauge fields have been instrumental in demonstrating topological phenomena in many physical systems, including photonics, cold atoms and acoustic waves. In our most recent paper, we demonstrate experimentally for the first time waveguiding by means of artificial gauge fields. To this end, we construct artificial gauge fields in a photonic waveguide array, by using waveguides with nontrivial trajectories. First, we show that tilting the waveguide arrays gives rise to gauge fields that are different in the core and the cladding, shifting their respective dispersion curves, and in turn confining the light to the core. In a more advanced setting, we demonstrate waveguiding in a medium with the same artificial gauge field and the same dispersion everywhere, where the only difference between the "core" and the "cladding" region of the waveguide is a phase shift in the dynamics of the gauge fields. The phase-shifted sinusoidal trajectories of the waveguides give rise to waveguiding via bound states in the continuum. Creating waveguiding and bound states in the continuum by means of artificial gauge fields is relevant to a wide range of physical systems, ranging from photonics and microwaves to cold atoms and acoustics.

Let us briefly describe the advanced setting of waveguiding of light by phase-shifted but otherwise identical artificial gauge fields. That is – light is guided in a core region that is made from the same material as the cladding, and has the same artificial gauge field as the cladding, with the only thing distinguishing between the core and the cladding being a phase shift in the synthetic gauge.



(a),(b) Schematic of the two dimensional waveguide array of sinusoidal trajectories displaying guiding by phase-shifted artificial gauge fields. All the waveguides have the same index profile and follow a sinusoidal trajectory with the same periodicity and amplitude (A), but the cladding (blue) and core (red) rows are shifted by a π phase. (c) Dispersion relation of the waveguide array depicted in (a). The z-periodicity of the structure gives rise to periodic dispersion relation (described by a Floquet spectrum). The blue lines represent the modes that are extended over the whole array, while the red lines represent the modes confined to the core waveguides. (d) Amplitude profiles for two of the modes that are mostly confined to the core waveguides. Their position in the dispersion relation is depicted in (c) as a red circle and a blue square. The red profile shows the special mode that has zero coupling to the cladding (as noted by the fact that it has zero energy in the cladding). For comparison, we plot a mode at a different k_x value (blue square), where the leakage into the cladding is evident.

The next figure shows our experimental results displaying waveguiding by phase-shifted artificial gauge fields, as appeared in [4]. We launch, into both of the core arrays, an elongated Gaussian beam tilted in the x-direction such that we control its wavenumber k_x. The lattice oscillation amplitude is 8μm. (a) Ratio of the power at the core to the total power in the array, measured at the output plane of the lattice, as a function of the launch wavevector, k_x. The red arrows mark the position of maximum core guiding calculated by continuum simulation, which clearly agrees with the experimental results. The blue horizontal lines mark the Brillouin zone (notice the expected peak replicas outside the Brillouin zone). (b), (c) Experimentally observed intensity profile at the lattice output for a propagating wavevector in (a) the unguided region (k_x marked in (a) with a square) and in the (c) guiding region (k_x marked in (a) as a circle).



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