Self-aligning Achromatic Light Transducers - SALT

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ABSTRACT

From the human eye to nanophotonics, the key to manipulating light for imaging, sensing, energy harvesting, and optical classical and quantum computation is refraction in inhomogeneous transparent material. Refraction is chromatic, different colours suffer different effects. This causes a crippling rainbow distortion or chromatic dispersion that becomes increasingly dominant the higher the imaging resolution and the stronger the optical field localization involved. We describe our development and testing of prototype super-refractors composed of specifically fabricated and processed solid-solution potassium-lithium-tantalate-niobate (KLTN). Results include achromatic miniaturized photonic light transmission and beam-size reduction, constraint-free nonlinear optics, and giant-refraction electrical control.

Keywords: Visible-light imaging; nonlinear optics; nanophotonics.

1. INTRODUCTION

Rainbows are one of the most fascinating phenomena we experience in our everyday life, but they signal one of the main hurdles in our ability to control and harness light: chromatic dispersion. The effect is rendered vivid when we look at red and green light from commercial LEDs through reading glasses: as we rotate our heads sideways, the red and green images will shift differently and even switch positions. This chromatic dispersion is not just a shortcoming of our glasses. Quite the contrary, it is a direct and fundamental consequence of how electromagnetic waves interact with transparent materials. The effect becomes ever stronger as the resolution of the imaging system grows or, equally, as the actual device is itself miniaturized. While photonic technology can overcome dispersion using monochromatic light, there are many practical situations in which polychromatic light is essential. Apart from standard vision, photography, microscopy, and astronomy, a specific example is multi-spectral imaging. In these cases, the absence of achromatic refractive elements forces us to use alternative and cumbersome solutions, such as large reflective telescopes instead of their simpler refractive ones. In the SALT Attract project, we developed and tested a prototypical achromatic refractor based on giant broadband optical refraction in a specifically engineered solid-solution ferroelectric crystal. The refractor is able to manipulate light across the entire visible and near-infrared spectrum with negligible chromatic dispersion and diffraction in a wide range of regimes. The SALT refractor is furthermore self-aligning, can be activated and deactivated electrically, and can be used both for linear optical functions, such as the aforementioned multi-spectral imaging, or in nonlinear optics, where absence of chromatic walk-off leads to constraint-free wavelength conversion.

Our SALT achromatic refractor makes no use of metamaterials, metasurfaces, or any form of artificial volume micromanufacturing. Nor does it make use of metallic states, resonances, or strong absorption regimes. Rather, it taps into the hereto little explored realm of higher-dimensional topological defects that form as a full 3D system undergoes a symmetry-breaking phase-transition. In our case, the KLTN crystal passes, at room-temperature, from a paraelectric to a ferroelectric state.

In our SALT project, we have

- developed a comprehensive model to understand and harness giant broadband refraction;
- developed a specifically tailored growth and post-fabrication processing method to achieve optical quality achromatic refractor elements;
- demonstrated a miniaturized achromatic telescope;
- demonstrated a self-aligning achromatic prism;
- explored how giant broadband refraction can be controlled electrically.

2. STATE OF THE ART

Miniaturization is a basic and persistent drive to innovation in photonics. Ever smaller and more performing lenses, waveguides, filters, telescopes, microscopes, and detectors encounter the apparently unsurmountable hurdle of a micrometric optical wavelength [1]. Focusing and manipulating light to below even the apparently huge scale of one micrometer poses major challenges. The hurdle is ever more tangible for polychromatic light, such as that from fluorescence, as behaviour becomes ever more wavelength-dependent the more miniaturized the device. A viable scheme to outdo this limitation is to make use of metamaterials or metasurfaces [2]. Here light resonantly interacts with materials that have artificially designed periodic subwavelength features to generate conceptually unlimited resolution and miniaturization. Metamaterials and metasurfaces, however, are based on resonance and only work for a very limited bandwidth, excluding their use as a generic broadband miniaturization strategy. A second strategy is to couple light to metals through so-called surface plasmons [2]. This promises a new miniaturized optical technology that, however, implies a step away from transparent light propagation in dielectrics and a step towards non-transparent electronics. A more general approach is simply to miniaturize the effective wavelength by increasing the index of refraction of a dielectric. This strategy is in turn haunted by its own built-in riddles. The first is that a high-index of refraction generally goes hand-in-hand with an optical resonance, a strongly absorbing and dispersive condition that does not allow propagation and certainly enhances chromatic aberrations. The second is that matching waves from a low index of refraction medium, such as vacuum or air, to a high index of refraction material, and vice-versa, involves strong Fresnel reflection: light will generally not enter a high-index of refraction device nor leave it. Ferroelectrics can overcome these limitations, forming the core of the SALT approach: giant refraction [3].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The SALT refractor we have developed represents a new promising optical platform for both linear and nonlinear photonics. In terms of linear optical propagation, light in the entire visible and near-infrared spectrum suffers strongly reduced diffraction (see Rayleigh Length in Tab.1). This forms the key to increased optical circuit miniaturization and to enhanced functionality in high-resolution image transmission. The absence of diffraction is accompanied by a strong reduction in effective chromatic dispersion, as measured through Snell law analysis (Chromatic Aberration, see Tab.1). Here the State-of-the-Art comparison is with the Zeiss Superachromat lens (a 20 cm assembly compared to the 2 mm SALT refractor). The SALT refractor also has the ability to self-align. This means that it will transfer light to a single point at the output facet irrespective of the input incidence angle (see Self-alignment in Tab.1). The KLTN based material is, in turn, not affected by a giant Fresnel Reflection at the input and output facets, this being a consequence of its underlying periodic inhomogeneous anisotropy (or alternating birefringence), while manifesting an overall standard absorption (see Tab.1).

Tab. 1. Broadband linear optics breakthroughs.

Property	SALT Refractor	State of the Art
Rayleigh Length (10μm Gaussian input @633nm)	>5mm	1mm (reference index of refraction n=2)
Chromatic Aberration (relative variation in lens focal length per μm)	<0.002 (1/μm)	0.003 (1/μm) (Zeiss Superachormat)
Self-alignment (sensibility of transmission angle on incidence angle)	<0.04	None
Fresnel Reflection (Intensity reflection coefficient on normal incidence)	<0.25	>0.92 (Fresnel Reflection for a giant index of refraction of n>26) 0.1 (glass without anti-reflection coating)
Absorption Coefficient (VIS-nearIR)	*<2 (1/cm)*	0.1 (1/cm) for industrial grade Lithium-Niobate @1064nm

Using pulsed laser sources now permits the harnessing of the SALT refractor as a support for nonlinear optical processes, such as second-harmonic-generation (SHG). The achromatic and diffraction-free nature of optical propagation in the material make an ideal setting for what can best be termed constraint-free SHG. For one, the absence of diffraction means that pump beams can be strongly focused into the sample without this causing a reduction in the effective active length of the process, while the achromatic nature of the beam kinematics strongly reduces the effects of chromatic walk-off. This allows SHG conversion to make use of non-resonant wavelength conversion processes, allowing hereto unprecedently broad angular, spectral, and polarization acceptance, as summarized in Tab.2.

Tab. 2. Broadband nonlinear optics breakthroughs.

Property	SALT Refractor	State of the Art
Effective Chi2 Coefficient (overall)	3500 (pm/V)	168 (pm/V) for commercial KTN
SHG Angular acceptance (external angle)	+-40 degrees	less than +-5 degrees
SHG Spectral acceptance	>100nm	<20 nm
SHG Polarization sensitivity	None	Type-I or Type-II phase-matching

4. PROJECT RESULTS

A first core result of the SALT project is the growth, processing, and testing of a miniaturized achromatic refractor made of KLTN (or KTN:Li). A snapshot of the refractor is reported in Fig.1. In this specific case, light from a commercial projector collected through a microscope objective that normally spreads and diffracts into its component chromatic components suffers an achromatic telescopic effect as it hits a zero-cut KLTN sample. All component colours follow the same path (red-lines and arrows in Fig.1). The crystal acts as an ideal refractor, as would be required in a telescope. Furthermore, its operation is also only weakly alignment-dependent, that is, the actual angle with which the sample is rotated relative to the overall beam propagation leads to negligible changes in the telescopic effect.

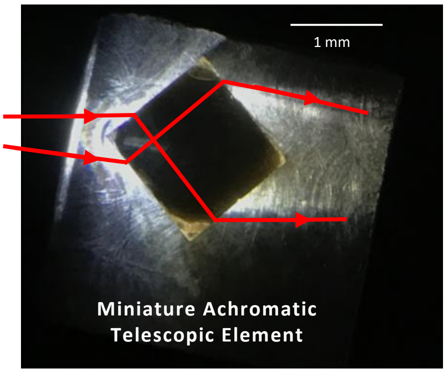

Fig. 1. Snapshot of the operation of an achromatic telescopic element achieved using a specifically grown and post-processed KLTN. White light from a commercial projector does not split up into its components that all follow the same trajectory (red lines).

A second core SALT result is the fabrication of more elaborate sculpted crystal samples to achieve the transfer of focused white light with no chromatic aberration and diffraction. The prototype achromatic prism prototype is reported in Fig.2. Here white light is focused onto one facet of the rotated prism and follows a path determined by giant broadband refraction (red lines and arrows), with no beam spreading or chromatic aberration. The transducer operates for arbitrarily large incidence angles, limited only by standard Fresnel reflection, so that the white light is funnelled from one facet to the another as if the space occupied by the transducer, for the propagating light, does not exist. The nature of the achromatic transfer of light can be directly appreciated by having the transferred light impinge directly on a sample corner on exiting the prism. The remarkable result is now a chromatic separation into colours on exiting the sample, since the corner is not able to efficiently support giant refraction (see Fig.3).

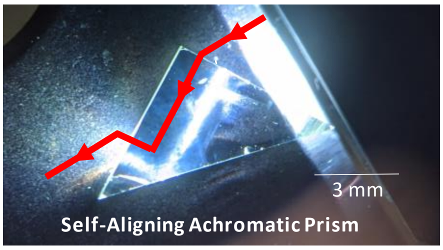

Fig. 2. When sculpted into a prism, the achromatic refractor is used to transduce light without diffraction and chromatic aberration, even for white light focused down by a high-aperture objective.

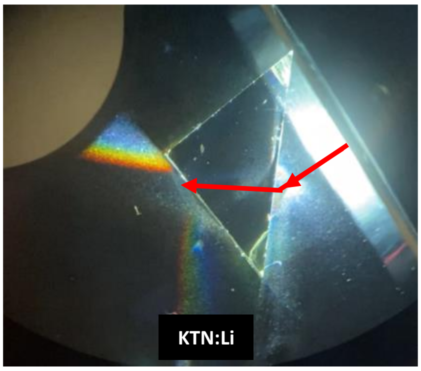

Fig. 3. Harnessing the achromatic prism to force the polychromatic light into a sample corner, now finally spreading into its underlying chromatic components.

Our SALT project was also able to demonstrate the control of giant refraction and hence achromatic light transfer using an electric field [4]. In this case the electric field is able to switch off the effect by causing the KLTN sample to form a disordered array of underling polar nanoregions, effectively causing critical opalescence (see Fig.4).

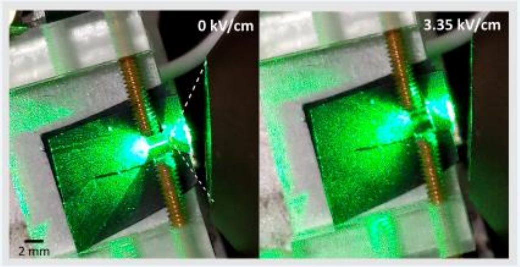

Fig. 4. Controlling the achromatic transducer electrically.

Another important SALT result is the demonstration of how the achromatic transducer can also be used to achieve constraint-free nonlinear wavelength conversion [5]. An example of the phenomenon is reported in Fig.5. Laser light from a pulsed source at 810 nm (the red pump ω) is focused onto a KLTN sample manifesting giant broadband refraction. The result is that light remains focused inside the sample, travels normal to the input facet, and exits from the sample in the form of converted light at 405 nm (the blue signal at 2ω). Remarkably, the effect depends weakly on the polarization, wavelength, and input incidence angle. The effect is in fact so strong that it occurs even without full phase-matching, the output polarization being the same as the input polarization.

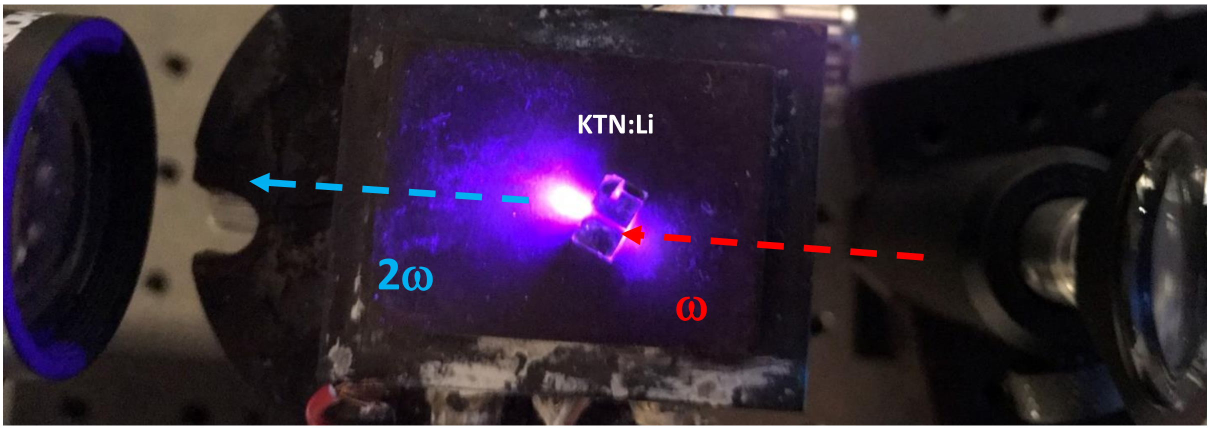

Fig. 5. Focused infrared light from a pulsed laser is now able to undergo strong wavelength conversion in the KLTN achromatic transducer irrespective of launch angle, polarization, and wavelength.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The SALT project has the aim of developing a new platform for optics and photonics based on giant broadband refraction to achieve miniaturized achromatic light manipulation. The basic principle has been observed, the concepts formulated, and even prototypical achromatic refractors have been designed and fabricated. The laboratory validation of the overall concept still needs to address spatially resolved thermal and electrical control (TRL 4). Furthermore, while the prototype is validated as a miniaturized achromatic beam condenser, as would be ideal for solar energy harvesting, its implementation as an imaging device still requires the validation of image quality transfer (TRL 4). What is missing at the present stage of development to reach TRL 5-7 is then the assembly of an achromatic device, specifically, an achromatic self-standing telescopic objective able to be mounted onto a detector or camera system. Here the challenge is in designing the accompanying miniaturized electrical and thermal control and housing.

5.2. Project Synergies and Outreach

In the drive towards TRL 5-7, the SALT team needs to team up with a number of new key partners. These are

- an academic partner in the field of chemistry and material science to develop a KLTN low cost high-yield growth procedure;
- an industrial partner to design a large-scale crystal production process;
- an academic partner to design the miniaturized thermal and electrical control units;
- an industrial/commercial partner to design specific integrated imaging product solutions.

Teaming up with other ATTRACT funded projects can play a key role in the TRL ramp-up, especially as regards to projects aimed at developing specific detection arrays for visible and infrared light. In building a possible ATTRACT Phase 2 TRL ramp-up initiative, one basic contact, dissemination, and outreaching strategy is based on producing direct short video or even live demonstrations of the remarkable optical properties of the SALT refractor. We have already implemented this strategy in scientific dissemination, whereby our articles are normally accompanied by direct video footage of the functionalities discussed. The approach seems all the more appealing as our technology has to do with everyday light sources (lamps, the sun, projectors), and involves visible effects that not only signal the underlying physics, but also capture in a visible way our common creativity and imagination.

5.3. Technology application and demonstration cases

An attract Phase 2 will focus on specific applications based on achromatic refractors. Principal among these will be the design of a miniaturized multi-spectral CMOS camera where the conventional prism redirector is substituted with a SALT prism refractor. Absence of diffraction, chromatic dispersion, and the ability to route light with arbitrary angles will allow a substantial miniaturization of the device. Multi-spectral imaging is at the heart of core European challenges. For example, it allows a direct monitoring of temperature, food quality, the analysis of artifacts and monuments, and the evaluation of environmental pollution. In photonics and optoelectronics, miniaturization to nanophotonic circuits without using metals is key to reducing absorption constraints on future information and computation technology, while the achromatic white-light self-aligning transducers emerges as a key technology in super-efficient miniaturized and portable/moving solar panels, where alignment to the light emitting source is impractical if not impossible. Finally, a broadband achromatic optical transducer appears as a key ingredient in high resolution imaging using miniaturized microscopes, as can be envisioned in remote sensing applications for in vivo medical diagnosis. In terms of high-resolution telescopes, a basic application of the SALT refractor is in the realization of a miniaturized high-aperture telescope with the goal of being mountable on miniature satellites such as CubeSats. Here the benefit to the European citizen stems from an increased awareness, security, and exploration of our surroundings with cost effective and reliable emerging technology.

Both in terms of medical and space sectors, the SALT refractor represents an innovative material platform, a form of physical infrastructure that can greatly benefit in a widespread European scale initiative.

A wholly parallel implementation initiative is in enhanced nonlinear photonics, where the design and development of miniaturized and rugged wavelength converters can be instrumental in detecting images in the infrared region. Here the applications can range from eye-safe lidar sensors to security and transport applications.

5.4. Technology commercialization

The SALT team commercialization strategy is based on developing a plug-and-play add-on to existing marketed devices. The example is the aforementioned miniaturized CMOS multi-spectral camera. In these terms, a ramped-up (TRL 5-7) SALT refractor can be considered market-ready. A wholly different story is when considering truly revolutionary designs, such as a miniaturized high-aperture telescope. Here a specific commercialization strategy is still unclear.

5.5. Envisioned risks

Foreseen risks associated to the SALT initiative are

- crystal growth and production costs, the envisioned mitigation strategy is the development of low-cost large-scale production;
- alternative competing technology, the envisioned mitigation strategy is an initial focus on market-ready plug-and-play applications.

5.6. Liaison with Student Teams and Socio-Economic Study

Housed in three large-scale public universities, an ATTRACT Phase 2 SALT initiative with additional industrial partners offers an ideal setting for Master Level student training. The SALT initiative will integrate its activity with leading industrial outreach organizations (local, national, and European) present on the territory to enhance direct interaction between industry and Master Students. Finally, the SALT team already in Phase 1 has a specific partner in charge of sampling and interacting with the scientific and intellectual community and ecosystem monitoring. In a Phase 2, this partner will also form the liaison link.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] Hecht, E., 2002, Optics, 4th Ed., Addison-Wesley, Reading, Mass., USA.

[2] Focus Issue, 2014, Not so small, Nature Photon, 8: pp. 877-972. https://doi.org/10.1038/nphoton.2014.282

[3] Di Mei, F. et al., 2018, Giant broadband refraction in the visible in a ferroelectric perovskite, Nature Photon, 12: pp. 734-738. https://doi.org/10.1038/s41566-018-0276-3

[4] Falsi, L. et al., 2020, Direct observation of fractal-dimensional percolation in the 3D cluster dynamics of a ferroelectric super-crystal, submitted to Phys. Rev. Lett. (APS)

[5] Falsi, L. et al., 2020, Constraint-free wavelength conversion supported by giant optical refraction in a 3D perovskite super-crystal, to appear in Communications Materials (Springer Nature)