Single Pixel Thermal Camera based on Liquid Crystal Resonant Structures

SPT-Cam

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ABSTRACT

Single pixel liquid Crystal (SPLC) layer combined with light responsive material such as semiconductor form what is called optically addressed spatial light modulator which is used for optical computing and image conversion. When LCs are part of a resonant photonic structure the optical readout can be made of narrow optical signatures and the strong electro/thermooptic effects in the LC reveal strong variations of the readout signal. Motivated by this approach several modes examined to demonstrate SPLC infrared/thermal camera using IR photosensors, VO_2 bolometric layer, porous Si, and graphite as thermal absorption layer. Semiconductor photosensors gave the best performance until now.

Keywords: Thermal Camera; Infrared Camera; Liquid Crystal Devices.

1. INTRODUCTION

Thermal and infrared (IR) imaging products, are becoming increasingly important in civilian sectors with the rise of new commercial and high volume markets such as automotive, surveillance, thermography, medical diagnosis, environmental sensing and IR imaging with smartphones [1]. It is believed that thermal imaging will play a key role in turning self-driving vehicles into consumer products. This trend created a cost-driven market in favor of uncooled infrared imaging systems. Unlike their cooled counterparts, which operate based on photo-generation and collection of electrons and holes, uncooled IR detectors sense the temperature change due to the absorption of IR radiation. The cooled detectors offer higher performance (higher resolution, higher signal-to-noise ratio, faster response) at a higher cost due to the need for cryogenic cooling. On the other hand, uncooled detectors offer cost effective solutions targeting the competitive low-end high-volume user market. Among uncooled detectors such as thermopiles, pyroelectric, and microbolometers, the latter are the most popular for infrared imaging purposes offering high resolution. Microbolometers are made of temperature-sensitive resistance materials, such as vanadium oxide for forming an electronic image exhibiting resolution on the order of 20 mK. However, the complexity of the readout integrated circuit and the need for the thermal leg structures to be electrically conductive with a high thermal resistance results in difficulty in scaling the device to smaller formats.

The purpose of this project is to develop a single pixel thermal/IR camera utilizing optically resonant structures in the visible range containing an active layer such as liquid crystal (LC). LCs are known to have strong electrooptic effect and thermooptic coefficient, particularly near their transition temperature. When LCs are combined with a resonant photonic structure such as a cavity, grating, or photonic crystal, the optical readout can be made of a very narrow optical signature (peak or dip) and the changes in the refractive index reveal changes in the resonances. The narrower the resonances, the higher the sensitivity of the intensity changes to the temperature variations. This is the essence of the proposed concept.

During the course of the project we accomplished the following main results: (i) Optimized semiconductor/LC structure using different photosensor layers such as InGaAs and PbSe achieving contrast of 70:1, (ii) Demonstrating thermal imaging using IR absorptive layer made of graphite combined with blue phase LC, (iii) Obtained preliminary results on hybrid structures including porous Si photonic crystal combined with LC, and VO_2 layer combined with LC.

2. STATE OF THE ART

Thermal/IR cameras are usually divided into two types: the cooled and uncooled ones. The cooled ones operate based on photo-generation and collection of electrons and holes, are semiconductor based, while the uncooled ones sense the temperature change due to thermal effects. The cooled detectors such as thermopiles, pyroelectric detectors, and microbolometers (MBs), offer higher performance (higher resolution, higher signal-to-noise ratio, faster response) at a higher cost due to the need for cryogenic cooling [1]. The uncooled detectors offer cost effective solutions targeting the competitive low-end high-volume user market. MBs are the most popular for infrared imaging purposes offering high resolution, however, their complexity results in difficulty in scaling the device to small formats.

Different approaches for single pixel cameras were proposed in the literature including [2]: (i) spatially structured illumination, structured detection and a single-pixel detector to deduce an image, (ii) raster scan a spatially selective detector over the field of view and rely upon the temporal analysis of the back-scattered light to give the intensity of every pixel in the image, (iii) the use of aperture coding which uses a series of binary transmission masks applied using a spatial light modulator to the image formed by a lens, and a single detector to measure the transmitted intensity. New materials such as Graphene, 2D chalcogenides and others combined with plasmonic structures are emerging as highly sensitive infrared detectors [3].

The use of LC optically addressed spatial light modulators (OASLMs) as a single pixel device for image conversion has been demonstrated in the visible range [4,5], however conversion from infrared to visible started to appear only lately [6-9]. Some approaches used the IR absorption of the LC combined with cavity [10,11] and another used black carbon paper to absorb the heat and convert it into coloured signal using blue phase LC [12].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Our approach overcomes the complexity of pixilation and the high cost associated with it, by using a single pixel thermal/IR sensing layer combined with optically resonant LC structure so that the reflected/transmitted visible light regenerates the thermal/IR image in the visible range which can then be detected with a standard Si camera. LCs have strong electrooptic (EO) effects and thermooptic (TO) coefficient (TOC), particularly near their transition temperature. The refractive index (RI) variation upon applying few volts is of the order of their molecular birefringence which is typically 0.1-0.3, but can approach 0.5-0.7 with special LC compounds. Their RIs and birefringence are experiencing a critical behavior with temperature in the visible range [13]. The TOC for the two principal RIs is expressed as:

$$\frac{dn_{\|,\perp}}{dT} = -B \mp \frac{c_{\|,\perp}\alpha\Delta n_0}{T_c}\left[1-\frac{T}{T_c}\right]^{\alpha-1} \qquad (1)$$

where $n_{\|,\perp}$, are the RIs along and perpendicular to the LC molecules (see figure 1a) and the difference is the molecular birefringence $\Delta n_m = n_\| - n_\perp$, and the constants $c_{\|,\perp} = 2,\ 2/3$. As an example, typical values of the different constants for Merck LC E7 are: $A=1.75;\ B=5.36x10^{-4};\ \Delta n_0 = 0.24;\ \alpha = 0.377;\ T_c = 333K$. Equation 1 shows that at room temperature the TOC for $n_\|$ is around -0.003 RIU/K and near the transition it approaches -0.01 RIU/K; wherein for the birefringence it is larger by a factor of x4/3. When LCs are combined with a resonant photonic structure such as a cavity, grating, or photonic crystal, the optical readout can be made of a very narrow optical signatures (peaks or dips) and the changes in the refractive index reveal shifts in the resonances. The narrower the resonances, the higher the sensitivity of the intensity changes to the temperature variations [14]. This is the essence of the proposed concept. In one mode of the device an IR absorption layer is needed and meant to be a layer similar to the ones used in uncooled thermal detectors such as pyrometers or bolometers or could also be based on a semiconducting effect that generates photocarriers. The IR image creates voltage distribution over the LC layer which can then be read with visible light. A 2nd mode of the device uses an IR absorption layer which causes heating, thus causing the LC molecules to re-orient following the temperature distribution. A 3rd mode of the device does not use an IR absorbing layer, but uses the fact that LC molecules have some absorption themselves in the IR region, or they can be doped with a material that absorbs the IR such as plasmonic nanoparticles.

4. PROJECT RESULTS

The schematic structure and testing setup maybe understood from Fig.1. The LC layer is between two substrates coated with several layers including transparent conducting electrodes (TCEs), alignment layers, and one substrate has the IR absorbing film. The resonant photonic structure can be formed on one substrate such as in the case of guided mode resonance (GMR) [14], or on the two substrates such with photonic crystal or cavity structure. The IR absorption layer could be a semiconducting photosensor, bolometric or pyrometric layer, or simply a black IR layer that converts the IR radiation into heat. In the 2nd mode the IR absorption of the LC may also be used to generate variation in the LC structure. The polarized beam splitter is a must for many LC modes that depend on retardation modulation, however there are modes where this is not necessary such as with helical or scattering mode LC or using cavity or the GMR.

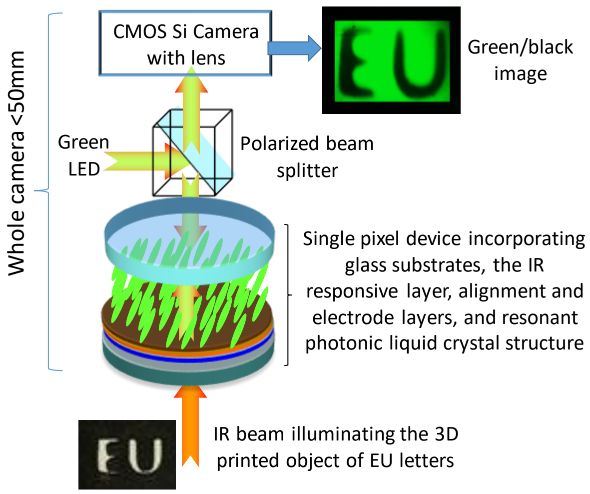

Fig. 1. Schematic of the thermal/IR single pixel imaging device integrated into Si camera. One example of IR illuminated object (EU letters) is shown as imaged with CMOS camera in green/black image in the 1st mode. The IR photosensor is a semiconductor sensitive to the SWIR range. Contrast is 70:1.

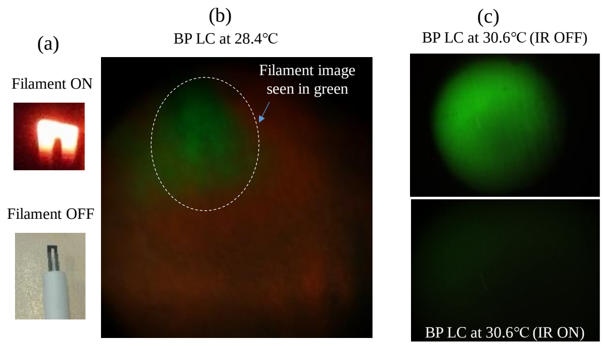

Fig. 2. Thermal imaging using 2nd mode in which a blue phase LC, which is resonant by itself is combined with Graphite layer (300nm thick) deposited on Si substrate as an IR absorbing layer. The heat generated in the IR causes the LC circular Bragg reflection peak to change from red to green. (a) Images of the IR source used (IR-Si207) at ON (top) and OFF (bottom) states. In (b) the filament image is seen in green over red background when the device is held at 28.5 °C. In (c) the device is held at 30.6 °C showing the strong green colour intensity (top) and almost extinguished (bottom) when the IR is ON.

In the 2nd mode we used blue phase LC. This phase has a 3D helical structure exhibiting selective reflection peaks when the wavelength corresponds to the helix pitch. Near the transition temperature from Cholesteric to the Blue phase I around 28 °C it is highly sensitive to temperature variations. As it can be seen in Fig.2., an MWIR image of the filament of IR source is shown as green image on red background using white light reading. At the lower temperature the colour is blue, then it becomes red as the pitch increases with temperature, then transforms to blue phase II exhibiting a green colour (see sequence in Fig.3.) and finally to the isotropic phase, meaning it will become dark, a fact that explains the almost complete extinction state shown in Fig.2c. (bottom). The extinction is seen because the reading uses PBS. In Fig.4., we show different images of patterns prepared using 3D printer (left mask) using the 1st mode with the SWIR photosensor being a semiconductor. The reading light was a green LED which is why the images are in green/black.

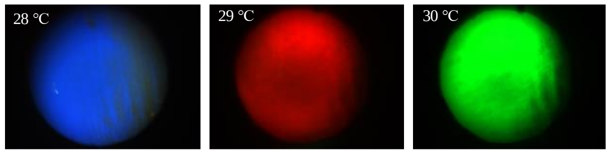

Fig. 3. Colour sequence variation of the blue phase LC as temperature increases, to explain the response to IR in Fig.2.

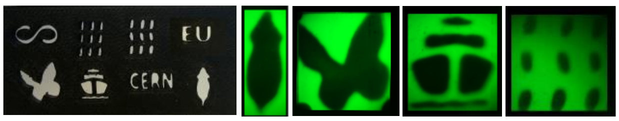

Fig. 4. Mask of different shapes (left) and the IR images obtained in the 1st mode using green LED and CMOS camera.

To check the 3rd mode of operation we have used a 1D photonic crystal made of porous Si (p-Si) as shown in Fig.5., (left) composed of two stacks of high and low porosity layers and a defect layer with higher porosity in between. The structure exhibits reflection band between 650-850nm and a defect state (dip) at around 770nm. The idea behind this is as follows: when the LC infiltrates the structure it will modify the effective refractive index both of the mirrors and the defect layer [15] so the reflectivity band with the defect state is expected to shift and therefore strong colour variation is expected. Under MWIR illumination we expect the LC to get heated due to its own absorption bands (Merck E7) in this range of the spectrum. Fig.5., shows two white light images of the device obtained without and with MWIR illuminated the Si side through a slit. It is seen that the colour of the device changed almost over the whole area upon irradiating the IR through the slit, however the slit image itself is not that sharp. The reason is believed to be first due to little infiltration of the LC in the whole p-Si structure and 2nd due to heat diffusion in the Si substrate, which has high heat diffusion coefficient.

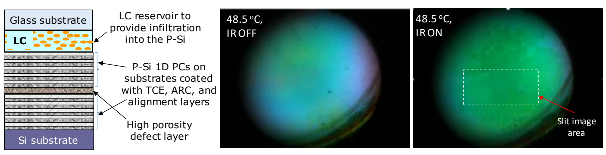

Fig. 5. Porous Si 1D photonic crystal/LC device (left) and the images read from the glass side using white light at IR OFF and ON. Due to heat diffusion in the Si substrate the slit image is not clear and the whole area changes colour quickly.

To overcome this problem, we are planning a device with much less heat conductivity layer in between the Si surface and the p-Si structure. Increasing the porosity will improve the LC infiltration, the sensitivity to the IR and the thermal isolation from the Si substrate. Pixilation is another approach to improve resolution and avoid heat diffusion, similar to the problem of photocarriers lateral diffusion that exists in the 1st mode when semiconductors are used. Pixilation also reduces the capacitance and the dark current. It can be done in one lithography step without affecting the device scalability or cost.

5. FUTURE PROJECT VISION

Our vision is to arrive to several products utilizing the concepts outlined in our project as per the infrared range to be detected and first to concentrate on two main products and that is a camera for the short wave infrared (SWIR) range and one for the Mid-wave infrared (MWIR) which is also called the thermal range.

5.1. Technology Scaling

During phase 1 we have validated the technology in the lab and achieved TRL 4 in two regions SWIR and MWIR. In the next phase our plan is first to achieve technology demonstration in a relevant environment (TRL 5 and 6) that is a single pixel SWIR camera used for night vision applications and MWIR camera used for medical thermography. Next the plan will be to build prototypes of SWIR and MWIR cameras packaged in a small format with the IR sensor/LC device attached to a CMOS camera and functioning in industrial, medical or remote sensing environment (TRL 7). As the technology uses other well established technologies such as the IR/thermal sensor industry, LCD industry and existing CMOS cameras, there is no special problem is scaling the technology up to mass production for lowering the cost.

5.2. Project Synergies and Outreach

The project is already done jointly between two organizations, Photonicsys Ltd and Universidad Autónoma de Madrid as well as Ben-Gurion University is external vendor, which can become a partner in phase 2. For phase 2 consortium two or more partners will be added from the field of IR/thermal sensors. Some funded projects from ATTRACT phase 1 can be relevant as they are developing IR sensors with special characteristics such as the project titled “Carbon quantum dots/graphene hybrids with broad photoresponsivity” (BANDPASS) and also “Transformational infrared detectors for medical and environmental sensing” (TIMES).

5.3. Technology application and demonstration cases

Thermal/IR cameras have applications in many fields, for example in detection of breast cancer, gas and fire, SWIR can be used in food inspection, seeing through fog and for night vision, hence its important also for autonomous cars vision. For the latter, thermal/IR imaging could step in to solve the low light problem at night. We shall start from lab demonstrations, then will move into night vision applications and next into body thermography and perhaps the option for breast cancer detection. As our device is integrated with a CMOS Si camera, we shall interface it to a mobile phone camera. As a low cost device that can convert any smart phone into thermal/IR camera, it will be revolutionary solution. Collaboration with companies and research groups in the EU will take place to develop the different applications.

5.4. Technology commercialization

There will be commercialization board dealing with all issues related to marketing and sales. Commercialization will be followed in two channels; one is developing the single device with means to attach it to smart phone. The number of mobiles will approach 7B in 2023, meaning if the device is sold for 200 Euros for 0.1% of the market, our annual sales will be 1.4B Euros. Companies such as Huawei and Apple are eager for accessories that can be integrated into their phones so one approach will be to get their interest in purchasing it or sell them a licence. The other approach will be to develop the whole camera and show its applications to the industry, medical doctors, agriculture, remote sensing, autonomous cars industry and homeland security.

5.5. Envisioned risks

Since the technology uses an already existing and well established technologies such as the LCD industry, thin films deposition and crystals growth, we do not anticipate any special risks in scaling it up to mass production. The only concern is the speed and resolution limitation for the mode that is based on IR absorption and converting into heat both using the LC itself as the absorption layer and using an additional absorbing layer adjacent to it. The speed depends on the thermal relaxation time which is usually in the milliseconds till seconds range, while the resolution depends on the thermal diffusion coefficient or the photocarriers lateral diffusion in the case of semiconductor. To resolve the speed issue we plan to use materials with short thermal relaxation time while for the resolution issue will divide the IR responsive layer into pixels separated by heat insulation walls. It is true that then the device becomes pixelated, however these are passive pixels and read in-parallel as single pixel. Besides, the option of using semiconductors as IR photosensitive layer is a good solution both for the speed and the resolution as we already demonstrated it using InGaAs photosensor.

5.6. Liaison with Student Teams and Socio-Economic Study

Graduate students both M.Sc and PhD were involved in different aspects in Phase 1. In Phase 2 we shall strengthen this activity further by having teams working together on sub-projects. We shall appoint a person responsible for academic relations to work with M.Sc teams from the different universities.

The dissemination plan was prepared by the consortium in collaboration with members of the Board of Commercialization, who has the responsibility for marketing and sales. The consortium coordinator (Photonicsys Ltd.) will also track dissemination activities such that the European Committee can follow the progress in the reports. Public outreach is becoming a key element of scientific endeavour. Academic and industrial researchers can play a major role in promoting science education and science literacy. Proper communication between the partners and the public as well as the ATTRACT Phase 2 management is crucial. Ensuring such communication is one of the tasks of the project management.

6. ACKNOWLEDGEMENT

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