Enhanced Medical Endoscopic Detection and Sensing with Ultra-Bright Light (MEDS-Light)

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ABSTRACT

Medical endoscopy is critical for minimally invasive surgical procedures in the body, but high-end systems still rely on legacy lamp technology for illumination. This project develops a modern alternative light source with one or two orders of magnitude brightness enhanced LED light using fluorescent-converted light concentration. Extended spectral coverage and dynamic profiling with multiple fluorophore-host systems further enable contrast for the surgeon to better visualise disease tissue. This novel light source technology offers life-enhancing healthcare outcomes, a more environmentally friendly and low maintenance light technology, and can further address many other illumination and excitation applications.

Keywords: Light source technology; endoscopy; healthcare; illumination; excitation.

1. INTRODUCTION

Minimally invasive surgery based on medical endoscopy continues to grow in importance due to a rising elderly population and the prevalence of diseases requiring endoscopic procedures. Light sources deliver illumination via a fibre optic bundle embedded in the endoscope and, e.g. in laparoscopy in the large abdominal cavity, they must be high brightness. The clinical gold-standard is the xenon arc lamp, it is a legacy technology with a static spectrum and short lifetime thus needing regular replacement. It cannot be readily displaced by modern light emitting diode (LED) sources whose relatively high divergence limits their ability to couple to fibre.

This project develops an ultra-bright light source that takes high-power arrays of LED light with high divergence and enhances light brightness by one or two orders of magnitude using fluorescent-converted light concentrated in light guides. Furthermore, multi-fluorophores can be used to extend the light spectral range and allow dynamic spectral profiling, enabling contrast enhancement for the surgeon to better visualise disease tissue and anomalies. Our project goal is to develop this ultra-long lifetime bright and spectrally dynamic light source as a modern replacement for out-dated lamp technology with societal gain in life-enhancing healthcare outcomes combined with the benefits of an environmentally friendly and low maintenance (low cost of ownership) light technology.

In this project, we have made major advancements towards our technological development and application related goals:

- We have developed robust mechanical packaged brightness-enhanced light sources;
- The developed packaging incorporates a novel thermal management solution that allows for efficient high-power operation with a scalable solution for the dissipation of internal heat generation;
- Different fluorophore-host light-guide systems are tested for spectral extension;
- A further innovation is made for conversion of the thin rectangular output face of the light source into a circular cross-section for matching to the endoscope using a fibre-bundle convertor;
- The prototype device developed is suitable to conduct initial endoscopic medical trials and on a pathway towards commercial viability.

Whilst the bright-light device has a key application for enhanced illumination in medical endoscopy, the spectral diversity and low cost bright visible light source has potential application in other sectors and applications. These include other illumination applications e.g. display, projection and free-space communications, and excitation applications e.g. low-cost visible source for laser or maser pumping to displace current extremely expensive and limited power visible laser pump solutions.

2. STATE OF THE ART

The light emitting diode (LED) has revolutionised lighting and many commercial and industrial applications due to high energy efficiency, ultra-long lifetime (30,000hrs), good colour range (across the visible and beyond) and very low cost (<$/W). Unfortunately, its highly divergent spatial output means LED light has relatively low brightness *(defined as power per unit area per unit solid angle, ~0.1 W/mm^2.sr)* and it fails to compete with lamps and lasers for bright illumination or excitation applications. Lamps (e.g. xenon arc lamps) provide relatively bright sources of white light for high-end medical endoscopic illumination, display and projection, but their low efficiency, short lifetime (~500hr), and lack of dynamic spectral profiling are problematic. Lasers are by far the brightest light sources but for multi-watt visible light they are extremely expensive (~$100,000) and their narrow spectral extent makes them mismatched for endoscopic (and other) illumination and spectroscopic applications. With its extremely favourable properties and low cost, if LED light could be made considerably brighter it could supersede lamps in medical, and other markets e.g. display/projection and excitation applications.

Our light source developed for this project constitutes just such a step-change with its combination of brightness, spectral control, low cost and long lifetime. Its primary development is to compete with lamp illumination technology for use in medical endoscopy where direct LED light cannot compete since its high divergence limits the ability to couple sufficiently high power to an illumination fibre system embedded in endoscope.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

This project advances new brightness-enhanced light source technology to displace the current “gold-standard” xenon arc-light source in high-end medical endoscopy (e.g. laparoscopy). With approximately 50 times longer source lifetime and higher reliability our solid-state light solution would enable elimination of on-going lamp replacement costs and cumbersome replacement procedures with associated maintenance down-time. Higher brightness light system can use smaller bore endoscopes which entail a less invasive cut for insertion with shorter healing time. Provision of dynamic and reconfigurable spectral profiling of the light technology offers the surgeon lighting options to provide optimal surgical contrast resulting in enhanced clinical outcomes for surgical procedures. In summary, this new ultra-long-lifetime light technology provides an environmentally friendly alternative to replace old but clinical-standard lamp technology currently in use so providing improved patient safety and superior clinician diagnosis and patient outcomes.

The light technology is based on light emitting diode (LED) excitation of a fluorescent species (fluorophore) embedded in a solid-state (host) structure. A key innovation is configuring the fluorescent structure as a long, thin light-guide (Fig.1). The fluorescence light excited by an array of LED emitters over a long guide length (L) is trapped by total internal reflection and emitted from a thin (t) end face of the guide. This leads to a huge “geometrical” increase in light brightness (e.g. with length L=100mm and thickness t = 0.5mm; brightness enhancement area factor is L/t = 200). By this means the fluorescent light can be made considerably brighter than the LED pump light itself and at the same time generate a broad spectrum of new wavelengths. By configuring multiple fluorophore modules to further extend the visible spectrum with independent LED pumping, we envisage a ‘white-light’ source for endoscopic illumination with dynamic spectral profiling to enhance tissue contrast to the surgeon.

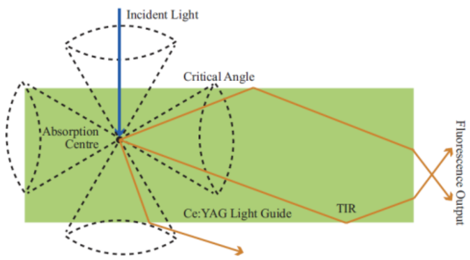

Fig. 1. Brightness-enhanced excitation light (high-power LED arrays) fluorescence-converted in a long (L), thin (t) light-guide. Total internal reflection (TIR) traps ~68% of fluorescent light emitted from thin end of light-guide with geometrical brightness-enhancement factor L/t ~ 100-1000.

4. PROJECT RESULTS

This project has taken innovative research of brightness-enhanced light and incorporated it into a commercial-style prototype product with thermally robust packaging. Innovative spatial reformatting of light source allows it to optimally couple to a medical endoscope.

4.1. Thermally managed bright-light modules with robust mechanical packaging for operation of light source in real-world (e.g. surgical) environments.

Some LED pump light (~20%) dissipates as heat in the light-guide which can lead to unstable temperature escalation and negatively impact performance especially at high light powers. The conventional solution to contact a conductive heatsink directly to the fluorescent crystal is problematic as it may reduce total internal reflection limiting its light-guiding. To overcome this problem, we developed the new thermal management concept of applying a reflective-coating to a large side-surface of the fluorescent light-guide and then thermally contacting a heat sink to that coated surface. The coating is thin enough for heat to diffuse to the metal heat sink but prevents direct contact of light-guide optical surface from the metal heatsink.

Our first prototype thermally managed light module is shown in Fig. 2. A plate with a set of high-power blue LED arrays is used to excite a long (L=100mm), thin (t=1mm or 0.5mm) fluorescent light-guide in thermal contact to a second heatsink plate (concentration ratio L/t =100 and 200). The two plates bolt together to form a simple robust thermally managed package. For initial (fundamental) efficiency tests the module was water-cooled, but ultimately would be air-cooled. The light-guide ends were left exposed for measurement purposes.

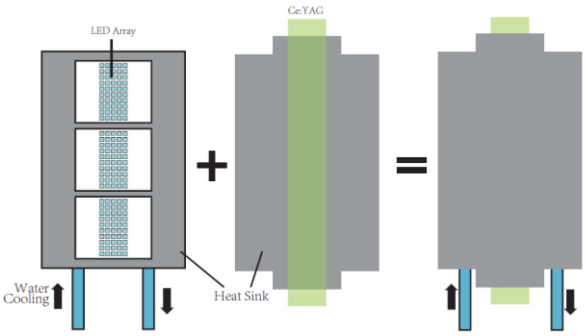

Fig. 2. Brightness-enhanced light modules with high-power LED arrays exciting thermally managed fluorescence light-guides in a robust, easy to manufacture and assemble package.

A number of these modules were built and tested using rectangular fluorescent slabs with different coatings (thin-film metal and dielectrics) and uncoated control samples. Initial tests were with Ce:YAG fluorescent material and later other fluorescent materials (see section 4.2). In addition to full LED pumping, in efficiency tests blue laser excitation was made at a single position (d) along the fluorescent light-guides relative to the emitter end and power and spectral output measurements were made. An example of spectral variation with excitation distance (d) is shown in Fig. 3, where it is seen as d increases the short wavelength end of the spectrum is progressively lost due to self-absorption effects. These studies allowed us to separate the intrinsic waveguide losses from self-absorption losses allowing us to better discern the coating losses. Dielectric coatings were found to be most effective and near lossless light guiding, whilst metal coatings had a small absorption giving greater guiding loss.

4.2. Increasing spectral coverage with fluorescent materials with different spectral range.

We tested other fluorophore-host combinations that allowed operation with shorter (green) and longer (red) wavelength spread to allow broader spectral coverage. As a high-risk aspect of our project, we also explored the prospect of blue fluorescent material pumped by UV LEDs. Unfortunately, whilst blue fluorophores were identified, no suitable optical quality fluorophore-host combination was identified at this stage. This problem was foreseen, and a contingency devised to utilise blue diode lasers instead, which are now commercially available at low cost. Whilst the blue laser light is discrete in wavelength(s) when combination with a dichroic mirror with our green, yellow and red spectrum brightness convertors it should simulate “white light” sufficiently well. The efficacy of this assertion will be tested in endoscopic application trials. By controlling excitation power for different fluorescent systems (and the power of blue lasers) we can provide *bright white-light with dynamic spectral profiling* for better tissue contrast for the medical endoscopic application.

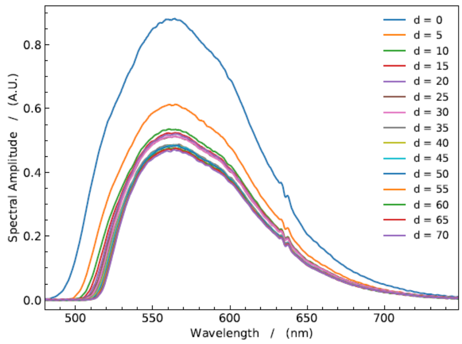

Fig. 3. Spectral variation of brightness-enhanced “yellow” light module as function of excitation distance from emission end.

4.3. Interfacing light-guide to medical endoscope cabling and endoscopy trials

The thin rectangular output face of the light-guide is mismatched to the medical endoscope. Free-space reshaping could be undertaken but this would be cumbersome, bulky and lead to a less robust device. To address this issue, we transformed the rectangular output of the light-guide geometry to a circular one in a single step using a bespoke linear-to-circular fibre bundle. The light-guide end face and fibre bundle were attached with index-matching optical quality adhesive. The result is a light output perfectly matched for direct coupling into the circular light cable that interfaces to the medical endoscope.

At this stage the goal was to attempt medical endoscopic trials on samples in-house and then, with clinicians in the Faculty of Medicine at Imperial College London operating in hospitals in London, to conduct early patient trials. Due to Covid-19 it was not possible to conduct these trials, but trials can proceed when situation is more suitable, if there is a Phase 2 to this project.

5. FUTURE PROJECT VISION

There are two levels of future vision we have for this project. The first future project vision, and the core application related to this current Phase 1 project, is to take the bright light technology through to endoscopy trials in a medical setting. The second future project vision relates to the further development of the bright light source technology itself to address a much wider range of potential applications, with fit-for-purpose commercial light product solutions. These include bright visible (and potentially non-visible) light illumination applications (e.g. display, projection, communications) and excitation applications (e.g. laser and maser visible light pumping).

5.1. Technology Scaling

The current Phase 1 project has advanced the brightness-enhanced light technology to TRL 3, at least terms of most aspects of performance and operation of the technology: we have developed a working packaged prototype design; we have gained know-how on thermal management of the technology with proprietary coatings and thermal contacting; the thermal management provides opportunity for, in principle, unlimited power scaling as the heatsink area scales with light-guide size.

The raising of the TRL of this technology in Phase 2 would be envisioned with two strands: a) the specific bright-light development for medical endoscopy; and b) the fuller development and scaling of the bright-light technology to address multiple other applications and market sectors.

For medical endoscopy, we have an “in-house” route to this market through the Faculty of Medicine at Imperial College London, with research scientists in medical endoscopy through to full practicing medical clinicians in surgical settings (NHS hospitals in London). We can guide the technology development supported by clinicians who can provide the ethical approvals to initiate patient trials (TRL 5/6). With further development and approved product design for patient use in hospital and clinics the technology may reach TRL 7/8.

We are keen to promote TRL development of the bright-light specification for other applications to meet a variety of technical and market-driven requirements. For laser pumping, we would need high power and potentially pulsed operation for high energy lasers. As a laser developer, we have significant know-how of the laser technology and market to take this commercially forwards to about TRL 5.

5.2. Project Synergies and Outreach

For project synergy, we would establish a strong collaboration with surgical researchers and clinicians in the Faculty of Medicine at Imperial College London.

We have a strong core team at Imperial College London, strengthened by the engineering expertise of Unilase Ltd which enables translation of scientific developments into engineering prototypes. We recognise the need to build a greater critical mass of our project in Phase 2, to meet the greater technical and market-driven challenges and we propose formally joining forces with a related research team at Northumbria University. The combined team will allow us to address a wider range of developments and explore new opportunities.

We would also welcome the input of other collaborators to support the technical success of this project. This might be other academic groups, but we are especially keen to establish links with businesses to help us achieve the fullest potential of this bright-light technology in market sectors.

We would look at public outreach to disseminate the medical and life-enhancing benefits and to society from the superior illumination technology and the environment benefits of replacing legacy lamp technology. We would promote the economic and technological benefits derived from our bright light technology, in international conference dissemination, but more widely to the public, for which we would look to establishing a website presence with product information, news items and white papers.

5.3. Technology application and demonstration cases

In Phase 2, we will provide a number of demonstration light modules addressing medical endoscopy. These systems would initially be trialled in-house then taken into clinical settings to address healthcare needs.

The innovation potential of this project is in its power to provide a step-change in the diagnostic quality of medical endoscopy for improved healthcare and dispense with short lived lamps with a more environment-friendly technology. This project therefore meets two of the policy priorities of the Europe 2020 strategy by addressing the challenges to benefit European society and their citizens in “Health, demographic change and wellbeing” and in “Climate action, environment, resource efficiency and raw materials”. These also match to **Megatrend: Personalised Medicine** including better identification and less invasive treatment of cancer, and **Megatrend: Zero Emissions** by reducing carbon footprint by replacement of inefficient lamp technology.

In Phase 2, we would look to broaden our ambitious to the wider development of bright-light technology. Specifically, we will scale power of the brightness-enhanced light technology to demonstrate high-power visible pumping of solid-state lasers. Our innovative thermal management methodology gives us unique potential for this scaling with dissipation of the significant heat generation. One key demonstration we will build will be a high power/high energy bright-light module for pumping of Alexandrite lasers. We are the world-leading group in diode-pumped Alexandrite lasers, but LED driven bright-light could be cheaper and more powerful. If the technology can be demonstrated with high efficiency, this would be beneficial for space technology for Earth Observation (lidar remote sensing), particularly vegetation lidar addressing sustainable forestry and agriculture and also more general altimetry e.g. bathymetry for mapping coastal water depth of importance for maritime safety. At Imperial, we have a long-standing programme on Earth Observation laser development supported by the European Space Agency (ESA) and would use that as a vehicle for satellite implementation, but also look at other commercial venture opportunities. This would address European Societal Challenges in sustainable agriculture and forestry; and wider climate action, environment and resource efficiency.

5.4. Technology commercialization

We are keen to develop the bright-light technology to enable commercialisation. Our consortium team has intellectual property (IP) in the form of patent at international stage. We have gained considerable know-how and product prototyping development, that form a good starting base to build towards commercial opportunity.

In the medical endoscopy / healthcare sector, we will establish early trials in medical settings through clinicians working in hospitals in London at Imperial. We already have some established links and plans prepared for this to go ahead. The prototype performance and TRL is still insufficient to compete with lamps, so we aim to raise the technology TRL further.

With an increased team we aim to address a wider bright-light development to address other market opportunities. We propose to look with our in-house Technology Transfer organisation at Imperial at routes to exploitation. This might be via licence, but Spin-Out company is an option as it might better capture the full value of a platform technology applicable across multiple market sectors. The PI on this project already has experience of Spin-Out and successfully taking a light technology from research lab to market.

5.5. Envisioned risks

Risks exist by the very nature of new innovative technologies, both at a technical level and at a market level. Key technology risk is not providing suitable competitive performance for the application, which we would mitigate by our increased team to resolve issues. Due to the wide application opportunities if one performance goal cannot be met to focus effort onto another opportunity/application.

5.6. Liaison with Student Teams and Socio-Economic Study

As a University research group, we already have wide experience of undergraduate and MSc projects and have indeed incorporated these into the Phase 1 project. We believe this light technology is very accessible for MSc student team projects. We would indeed, encourage projects from basic research, to evaluation of prototypes through to market research in key potential markets and applications. We would appoint a key experienced person on our consortium team to lead the interaction with MSc teams. We would hope to develop a larger team in Phase 2 to thereby provide the resource for upkeep of a project website and maintenance of project materials, news items, and outreach information.

6. ACKNOWLEDGEMENT

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