Micro-Optical Integration of Broadband Light Sources for High-Resolution Imaging

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INTRODUCTION

Micro-optical integration is a technique where various optical components with typical dimensions in the range of 0.3 mm to 1.5 mm are arranged on a free-space platform to deliver an integrated and compact optical module. Such integrated optical modules may collapse larger optical arrangements into a small formfactor to reduce the size of a system, or to increase the robustness of free-space optical architectures against shock and vibration, or to eliminate long-term drifts and misalignments. Micro-optical integration may also allow enhancing the performance or functionality of optical modules. For example, several semiconductor-based light sources operating at different wavelengths, such as Fabry-Perot laser diodes (LDs) or broadband Superluminescent Diodes (SLEDs), can be integrated into a compact optical module to deliver more power, multiple colors or broader optical bandwidth than conventional optical modules. In this work here, we are presenting an ultra-compact combined-SLED source with four broadband emitters at center wavelengths of 760 nm, 800 nm, 840 nm and 880 nm that are spectrally combined to an ultra-broadband output spectrum with a 3dB bandwidth of more than 165 nm around a center wavelength of 830 nm, delivering 15 mW of total power in a single-mode or polarization-maintaining output fiber. Such ultra-broadband SLED light sources enable the next generation of high-resolution biomedical imaging systems, for instance ultra-high-resolution (UHR) optical coherence tomography (OCT) systems with an axial resolution of better than two microns to achieve cellular resolution in tissue.

ARCHITECTURE OF OPTICAL MODULE

The optical module is a standard 14-pin butterfly package (housing 20.8 mm x 12.7 mm) with a ceramic optical bench that is mounted on top of a high-performance thermo-electric cooler (TEC). Each SLED chip is soldered onto an individual ceramic submount, which is then mounted onto the optical bench. The broadband light output of each SLED has a lateral single-mode and is emitted at the front facet of the semiconductor chip before being collimated by a micro-optical lens (1.0 mm x 1.0 mm) with an efficiency of more than 90%. Afterwards, the individual optical beams are collinearly aligned and spectrally combined by dielectric edge filters that, for example, transmit shorter wavelengths and reflect longer wavelengths. The combined optical beam is then coupled to a single-mode output fiber by means of a focusing lens, achieving a coupling efficiency of better than 50%. The optical bench also hosts a monitor photodiode (MPD) and an NTC temperature sensor such that the SLEDs are operated at a stable temperature. A photograph of an open module is shown in Fig. 1.

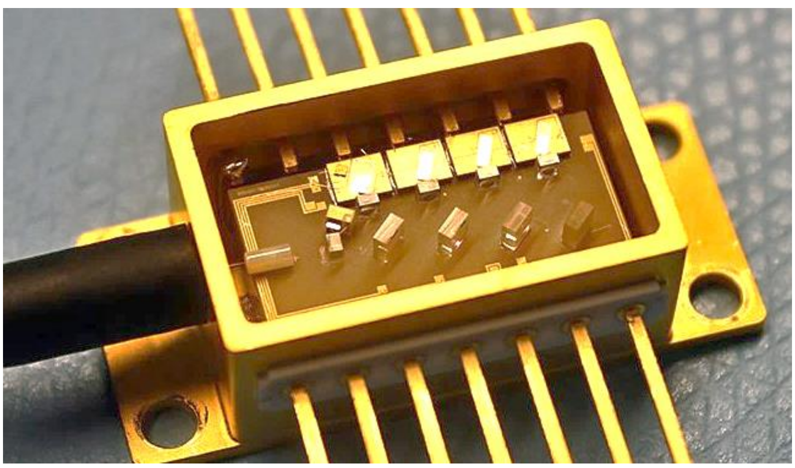

Fig. 1: Photograph of combined-SLED broadband light source in 14-pin Butterfly module

AUTOMATED MICRO-OPTICAL ASSEMBLY

The optical components are either passively or actively aligned by an automated assembly robot that performs automatic alignment with sub-micron precision and fixation of such components using UV-curable epoxy glues. This hybrid optical packaging platform (HOPP) and its alignment and gluing processes have been used for more than ten years by EXALOS and have been qualified based on Telcordia and MIL standards, demonstrating high levels of robustness against shock and vibration, temperature cycling, high- and low-temperature storage, or high-temperature operation with stringent hermeticity and humidity requirements. The alignment and positioning of any optical component based on pre-defined coordinates (passive alignment) is done with an accuracy of better than ±10 µm or 800 arcsec in rotation. Using optical powermeters or beam profilers (or any other instrument) as a feedback signal (active alignment), a positioning accuracy for an optical component of around 200 nm or 20 arcsec can be achieved, even including the shrinkage of the epoxy glues. Such high positioning accuracy in combination with supreme repeatability allows for high-yield manufacturing of optical modules even with complex optical architectures. Automated pick-and-place and alignment routines in combination with fully automated epoxy dispensing and curing processes allow for cost-efficient and high-volume manufacturing. Various lifetime tests carried out with such HOPP modules have demonstrated excellent long-term reliability over well beyond ten thousand operation hours.

ELECTRO-OPTICAL MODULE PERFORMANCE

The left-hand side of Fig. 2 shows the linear optical spectrum of the latest generation of combined-SLED sources in the 740-950 nm wavelength range, demonstrating a continuous optical spectrum with a 10dB bandwidth of nearly 190 nm and with a spectral flatness of better than -2.0 dB (~63%). The optical spectra of the individual SLED devices are indicated by the dashed lines. The right-hand side of Fig. 2 shows the Fourier transform of the combined ultra-broadband optical spectrum, which represents the coherence or imaging function. Here, the half width at half maximum corresponds to the coherence length of the source, which equals 2.4 µm in air. With a typical index of 1.35 for human tissue, this translates to an axial resolution of 1.8 µm. The sidelobes of the coherence function are given by the rather rectangular spectral envelope of the optical spectrum and are typically reduced during OCT signal processing, for example with spectral windowing. Another benefit of spectrally combining multiple broadband SLED sources on this free-space architecture (compared to fiberized couplers or combiners) is that the combined optical spectrum has a common and constant polarization orientation with an extinction ratio of more than 20 dB, which translates to superior imaging performance, especially for optically birefringent tissue.

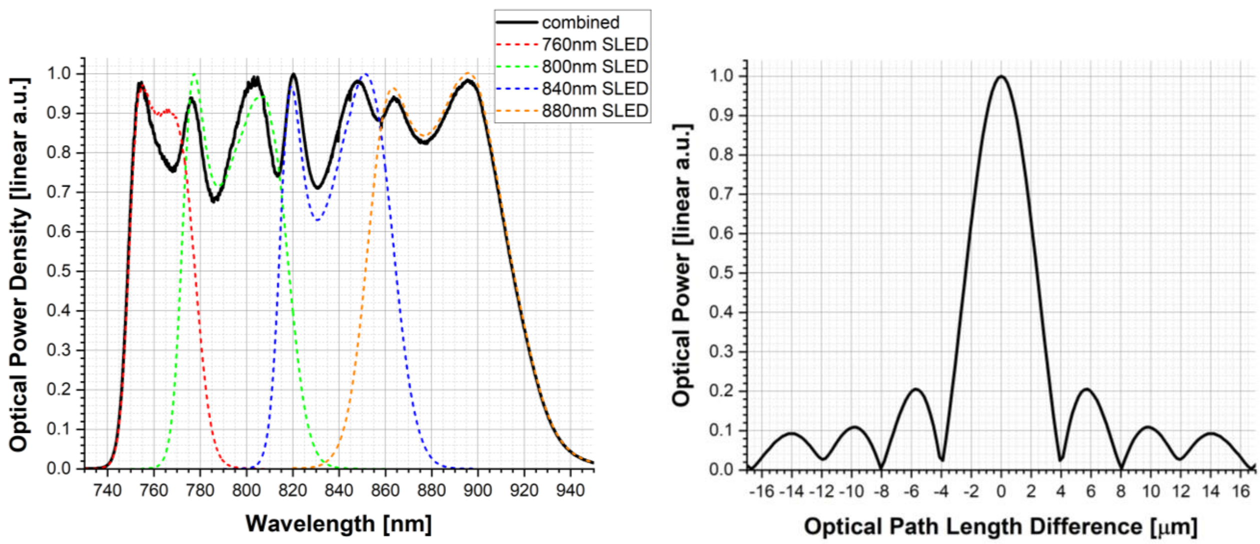

Fig. 2 Left: Optical spectrum of individual SLEDs (dashed line) and of combined source (solid line); Right: Coherence function of combined-SLED source with a coherence length of 2.4 µm (in air).