**Abstract**

In this paper, an overview of the EU FP7 project ISLA (Integrated disruptive components for 2 µm fibre Lasers) is given. The aim of ISLA was to develop a set of “building block” components and a “tool-kit” of processes to define an integrated modular common platform for two micron fibre lasers consisting of compatible and self-consistent active and passive fibres, fused fibre couplers and combiners, fibre-coupled isolators, modulators and high power pump laser diodes.

We also present results from our work on developing passive components for 2 µm fibre lasers. This includes high power pump combiners that have been tested up to 0.5 kW and combiners for in-band pumping of holmium lasers. Couplers for use as splitters, power monitors and wavelength division multiplexers have also been demonstrated. Wide-band couplers, with a coupling ratio that only varies ±12% over 400 nm, have also been developed to exploit the wide tuning range possible with thulium fibre lasers.

Research into different isolator materials was also conducted to find materials with large Verdet constants to be used in 2 µm isolators. Fibre-coupled isolators were then manufactured using a selection of these materials. Isolators that had insertion losses of < 1 dB and isolation of > 35 dB were demonstrated using PM and non-PM fibres. In the PM isolators, PER > 23 dB was achieved.

**Keywords:** Fiber Laser, Thulium, Holmium, Isolator, Coupler, Combiner, Fiber

1. **Introduction**

The ISLA project was a research and development project funded under the European Commission’s Seventh Framework Programme (FP7). The project started in October 2011 and ran to June 2015. The project was made up of a consortium of seven partners including University research groups from the Optoelectronics Research Centre, Southampton and Trinity College Dublin as well as industrial partners Gooch and Housego, II-VI Laser Enterprise, Rofin, Lumentum and Vivid components. The aim of the project was to develop a set of ‘building block’ components consisting of compatible and self-consistent active and passive fibres, fused fibre couplers and combiners, fibre-coupled isolators, modulators and high power pump laser diodes. Alongside the component development, the project aimed to develop a CW, a pulsed and a short pulse laser demonstration laser for use in applications testing.

Fibre lasers operating in the 2 µm region are of increasing interest for a range of applications, including laser machining [1-4], biomedical applications [5] and as pump sources for mid-IR sources [6-9]. The large mode area compared to 1µm fibre lasers combined with operation in an “eye-safe” region of the spectrum makes them particularly attractive. When developing fibre lasers at 1 µm & 1.5 µm, manufacturers were able to call upon enabling technologies used by the telecoms industry, but at longer wavelengths, including 2 µm, many such components are either unavailable or immature.

Therefore, as part of the passive component develop work in the ISLA project, we have developed new fused fibre components and optical isolators. In this paper we report on fibre-coupled isolators and wavelength-flattened couplers.

2. **Isolators**

Fibre lasers and amplifiers are highly susceptible to optical back reflections, which can cause destabilisations in the laser cavity through spurious lasing, and damage to laser components, most notably pump diodes. Reflections from the output...
end of the fibre (i.e. silica-air interface) can be easily removed by angle-cleaving the fibre, splicing an end cap onto the fibre or by application of an anti-reflection (AR) coating. These mechanisms are well studied and can reduce optical return loss (ratio of output power from a fibre to power of back reflected light in the core) to less than -60 dB. However, methods such as these are not always appropriate and cannot be used in all systems. In particular, master oscillator power amplifiers (MOPAs) need fibre-coupled isolators between stages to ensure reliable operation.

Isolators developed for high power applications at 1 μm rely on the use of Terbium Gallium Garnet (TGG) as the Faraday rotator material, which is the key element in an optical isolator. However, the performance of TGG decreases with increasing wavelength and is unsuitable for use at 2 μm. Therefore, new Faraday rotator materials must be found and new isolators developed for use in 2 μm fibre lasers.

Six potential materials for an isolator were tested and the Verdet constant measured over 1200 – 2400 nm using a supercontinuum source. The results are shown in Figure 1. The three materials with the highest Verdet constant (Bismuth thin film (Bi), Yttrium Iron Garnet (YIG) and Bismuth doped YIG (Bi: YIG)) were then developed into prototype isolators.

Figure 1. Verdet constant measurements for the tested isolator materials; (a) ZnSe, (b) CdMnTe, (c) YIG, (d) TGG, (e) Bi –thin film, (f) Bi: YIG
The isolators were fibre-coupled using both single mode (Nufern SM1950 and CorActive SCF 6/123) and polarization maintaining fibres (Nufern PM 10/130 GDF). The isolators were packaged in a high power housing and the insertion loss and isolation measured over 1700 – 2100 nm. The results are shown in Figure 2.

Figure 2. The isolation and insertion losses of the different isolators; a) SM Bi-thin film, b) PM Bi-thin film, c) PM YIG, d) SM YIG, e) SM Bi: YIG
The insertion loss of the devices ranged from 0.65 – 1.42 dB and the peak isolation varied between 33 – 40 dB. The variation of isolation with temperature was also measured and the results are shown in Figure 3.

![Figure 3. The change in isolation with temperature for the three different isolator materials](image)

3. WAVELENGTH FLATTENED COUPLERS

The broad emission spectrum of thulium fibres, which can extend from 1600-2200 nm makes a thulium fibre laser an excellent choice for building widely tunable fibre lasers [10]. An intra-cavity or external selective element, such as a Fabry-Perot filter [11] or an Acousto-Optic Tunable Filter (AOTF) [12] can be used to select the wavelength. Tuning ranges of >100 nm have been demonstrated [13] as well as all-fibre architectures [14]. These lasers were developed primarily with gas sensing and LIDAR applications in mind [13, 14] but have also found a potential use in optical communications [15]. Another application area for tunable swept lasers is in Swept Source Optical Coherence Tomography (SS-OCT) [16]. In particular, Thulium swept sources are particularly suited for non-invasive investigation of paintings [17].

However, over such wide tuning ranges, the coupling response of a standard fused fibre coupler can vary considerably with wavelength, to the extent that a 50: 50 coupler will behave as a WDM at certain wavelengths. To overcome this and allow for widely tunable lasers to be manufactured we developed wavelength flattened couplers with a greatly reduced change in coupling ratio with wavelength. These couplers were manufactured by pre-tapering the fibres, which had the effect of changing the propagation constants of the fibres. Figure 4 shows the coupling ratio change with wavelength for three 50: 50 couplers, with both output arms measured. The coupling ratio only varies by ± 12 between 1700 – 2100 nm.
4. SUMMARY

We have presented results from wavelength flattened couplers and fibre-coupled isolators that were developed as part of the ‘building block’ component development that was carried out in the ISLA project. Alongside these components, we have also developed high power pump combiners and low loss couplers designed for use in 2 μm fibre lasers. Alongside the passive component developments, the ISLA project has delivered highly efficient (>70%) Thulium and Holmium fibres, graphene based mode-lockers, amplitude modulators and tunable filters, silicon pulse pickers and pump diodes with > 38W in 105 μm fibre.

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REFERENCES