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Dual-wavelength tunable fibre laser with a 15-dBm peak power

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Abstract. **A high-power dual-wavelength tunable fibre laser (HP-DWTFL) operating in the C-band at wavelengths from 1536.7 nm to 1548.6 nm is proposed and demonstrated. The HP-DWTFL utilises an arrayed waveguide grating (AWG) (1×16 channels) and is capable of generating eight different dual-wavelength pairs with eight possible wavelength spacings ranging from 0.8 nm (the narrowest spacing) to 12.0 nm (the widest spacing). The average output power and side mode suppression ratio (SMSR) of the HP-DWTFL are measured to be 15 dBm and 52.55 dB, respectively. The proposed HP-DWTFL is highly stable with no variations in the chosen output wavelengths and has minimal changes in the output power. Such a laser has good potential for use in measurements, communications, spectroscopy and terahertz applications.**

Keywords: *erbium-doped fibre, arrayed waveguide grating, dual wavelength fibre lasers .*

1. Introduction

Generation of multiple wavelength outputs from fibre lasers has become the focus of increased interest for a number of significant applications including absorption measurements of trace gases and pH measurements, generation of high bit rate soliton pulses, high-resolution spectroscopy, and for fabrication of transmission sources in dense wavelength division multiplexing (DWDM) communication systems. Besides these applications, multiple-wavelength lasers are also used in generating microwave radiation for broadband wireless communication systems and also in sensor networks due to their narrow linewidth of the obtained microwave radiation.

Although there are many types of multi-wavelength fibre configurations, of particular interest to researchers is the dual-wavelength fibre laser (DWFL). It is widely used in applications requiring two or more closely spaced lasing wavelengths that are generated in the erbium-doped fibre amplifier (EDFA) employed as the gain medium for fibre lasers. However, use of the EDFA incurs a limitation due to its homogeneous line broadening, which causes low output powers as well as mode competition. There are, however, attempts to overcome these problems by cooling the EDFA with liquid nitrogen [1, 2], using an elliptical core in the erbium-doped fibre (EDF) [3], by using a polarisation-maintaining fibre Bragg gratings (FBGs) for specific wavelength selection and filtering [4], utilising a frequency shifter in the cavity [5], employing a distributed fibre Bragg (DFB) fibre laser source [6], using the four-wave mixing (FWM) effect as a stabiliser [7], optical injection Fabry – Perot lasers in the DWFL [8], and even dual-ring fibre lasers [9], etc. While these methods are successful to a certain extent in alleviating the problem of mode competition, their complexity and high cost still render them highly prohibitive. Using semiconductor optical amplifiers (SOAs), on the other hand, provides a viable solution to this issue, as the SOA is an inhomogeneous gain medium and thus can be used in the DWFL without causing significant mode competition via cross-gain saturation and strong homogeneous line broadening as in the case of the EDFA. However, SOAs themselves suffer from certain limitations, including a low power output and significant polarisation-dependent loss.

Recently of interest is the fabrication of high-power dual-wavelength laser sources (HP-DWFL) that can be applied in the areas of wavelength conversion using FWM effect [10]. Other applications are the generation of microwave signals [11] and generation of terahertz waves [12], which also require high power dual-wavelength fibre lasers. Existing erbium-doped fibres with high absorption coefficients at 980 nm and 1550 nm offer realisation of a high power dual-wavelength fibre laser, which is due to the ready availability of high pump diode lasers at 980 nm and also the low-loss coupler. There are reported works in this area where ytterbium is used to generate a high power dual-wavelength output at 1060 nm [13, 14] and a codoped Yb/Er was employed for generation at 1550 nm [15 – 17].

In this paper, we propose a continuous wave high-power dual-wavelength tunable fibre laser (HP-DWTFL) based on a ring cavity coupled to a booster amplifier, which can generate an output power of 15 dBm. The dual-wavelength output is produced by using an arrayed waveguide grating (AWG) together with optical switches (OSs) acting as the selecting element to provide a switchable fibre laser capable of generating wavelength spacings that can be tuned from 0.8 nm to 12.0 nm, which is the first of its kind to be reported.

2. Experimental setup

The experimental setup of the proposed HP-DWTFL is shown in Fig. 1. The system consists of a 5-m-long Metrogain EDF (Fibercore Ltd.) with absorption coefficients of 11.9 dB m^{-1} at 979 nm and 16.4 dB m^{-1} at 1531 nm which acts as the gain

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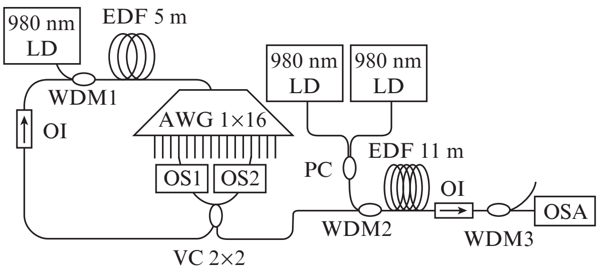

Figure 1. Experimental setup showing the various components of the HP-DWTFL:
(AWG) arrayed waveguide grating; (EDF) erbium doped fibre; (OSA) optical spectrum analyser; (WDM) wavelength division multiplexer; (LD) laser diode; (PC) pump combiner; (OI) optical isolator; (OS) optical switch; (VC) 2×2 variable coupler.

medium for the ring cavity. The EDF is pumped through a 980/1550-nm WDM (WDM1) by a 980-nm pump laser operating at 979 nm with an output power of 120 mW. The pump laser excites the erbium ion into higher states which is accompanied by amplified spontaneous emission (ASE) of output radiation at both ends of the fibre. The optical isolator forces the oscillation in the clockwise direction with the ASE being emitted on the right hand side and moving towards the arrayed waveguide grating (AWG). The AWG acts as a wavelength slicing element which operates in the 1550-nm region, and splits the ASE output into 16 different wavelengths (1×16 channels) having outputs from 1536.7 nm to 1548.6 nm with an interchannel spacing of 0.8 nm (100 GHz). Channels 1 (1536.7 nm) to 8 (1542.3 nm) are grouped together and are connected to the optical switch denoted (OS1). Similarly, channels 9 (1543.1 nm) to 16 (1548.6 nm) are grouped together and connected to the second optical switch (OS2). Each of the OS functions as a wavelength selector to choose a particular wavelength and combine them at the 2×2 variable coupler (VC) to generate the dual wavelength output. The OS used in this experiment operates optimally in the 1550-nm region and has a 500-ms switching time interval from each adjacent channel. One of the 2×2 VC output ports is then looped back to the 1550-nm input port of the WDM1 coupler via the optical isolator. Another port of the VC is then connected to the second EDF with a length of 11 m via a 980/1550-nm WDM2 coupler. The EDF in this section is of the same type as in the earlier case with similar specifications and acts as a booster amplifier in the 1550-nm region. Because the 11-m-long EDF needs a high pump power for optimum amplification, a pump combiner is used to connect two different 980-nm laser diodes giving a total pump power of 430 mW before it is connected to the 980/1550-nm WDM2 coupler. This EDF is then connected to an isolator and then to the WDM3 coupler before being connected to the optical spectrum analyser (OSA) for spectrum analysis. The WDM3 coupler inserted before the OSA is used as a filter to ensure that only the 1550-nm output enters the OSA. In short, the ring cavity as mentioned earlier, works as a source for the dual-wavelength output which is then amplified by the section of the experimental setup to generate the HP-DWTFL.

The uniqueness of this design is that the DWFL outputs can be chosen from any of the AWG channels, with the first signal coming from one of the channels (1 to 8) of the OS1 and the second signal coming from one of the channels (9 to 16) of the OS2 and can easily be switched from each adjacent channel by the OS within 500 ms. The channels can be set in pairs: 1 and 9, 2 and 9, 3 and 9, etc. For simplicity, the proposed experiment starts by selecting two wavelengths with the widest spacing and terminates in the case of the narrowest spacing. This is done by selecting channels: 1 and 16, 2 and 15, 3 and 14, 4 and 13, 5 and 12, 6 and 11, 7 and 10, and finally, 8 and 9.

As the gain media in the proposed setup we used EDFs that consist of an erbium ion with its well-known inherent homogeneous broadening effect, the dual-wavelength output tending to exhibit mode competition. The VC used in the experimental setup provides a cavity loss control mechanism to control the input coming to the second stage of amplification to ensure the exact peak value of the DWFL for the production of a balanced HP-DWTFL.

3. Results and discussion

Figure 2 shows the ASE spectrum at the output of the second 11-m-long EDF amplifier as a stand-alone amplifier. One can see from the figure that the maximum output power is centred at 1560 nm. This is due to the nature of the EDF whose gain profile shifts to the blue with increasing its length [18]. This spectrum shows that the amplification is maximal in the 1560-nm region. However, because the AWG used in this experiment is limited in its spectral range (from 1530 nm to 1545nm), the experiments are performed within this wavelength region. Nevertheless, the laser generation that can be achieved covers both the C-band and L-band regions. The nonuniform distribution of amplification in the 1530-nm region (see Fig. 2), as will be shown below, is the reason for the degradation of the side mode suppression ratio (SMSR) towards longer wavelengths as follows from the experimental results.

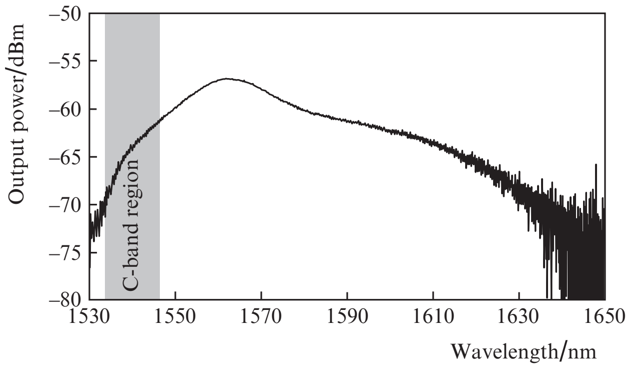

Figure 2. ASE spectrum of the booster amplifier.

Figure 3 shows the output of the ring cavity DWFL. The proposed experiment, however, faces two obstacles in fabricating balanced dual-wavelength fibre lasers. First, this is the mode competition which can be significantly reduced by the adjustment of the cavity losses inside the ring cavity. This is achieved by controlling the cavity losses in the ring cavity with the help of the variable coupler (VC) which allow the exact amount of power inside the cavity between the two wavelengths to be controlled. The balanced dual-wavelength output from the ring cavity is then amplified by the booster amplifier to generate a high power dual-wavelength fibre laser. The second issue is due to the gain profile of the booster amplifier which is not flat, and thus the output after amplification will tend to be unbalanced. This second problem is

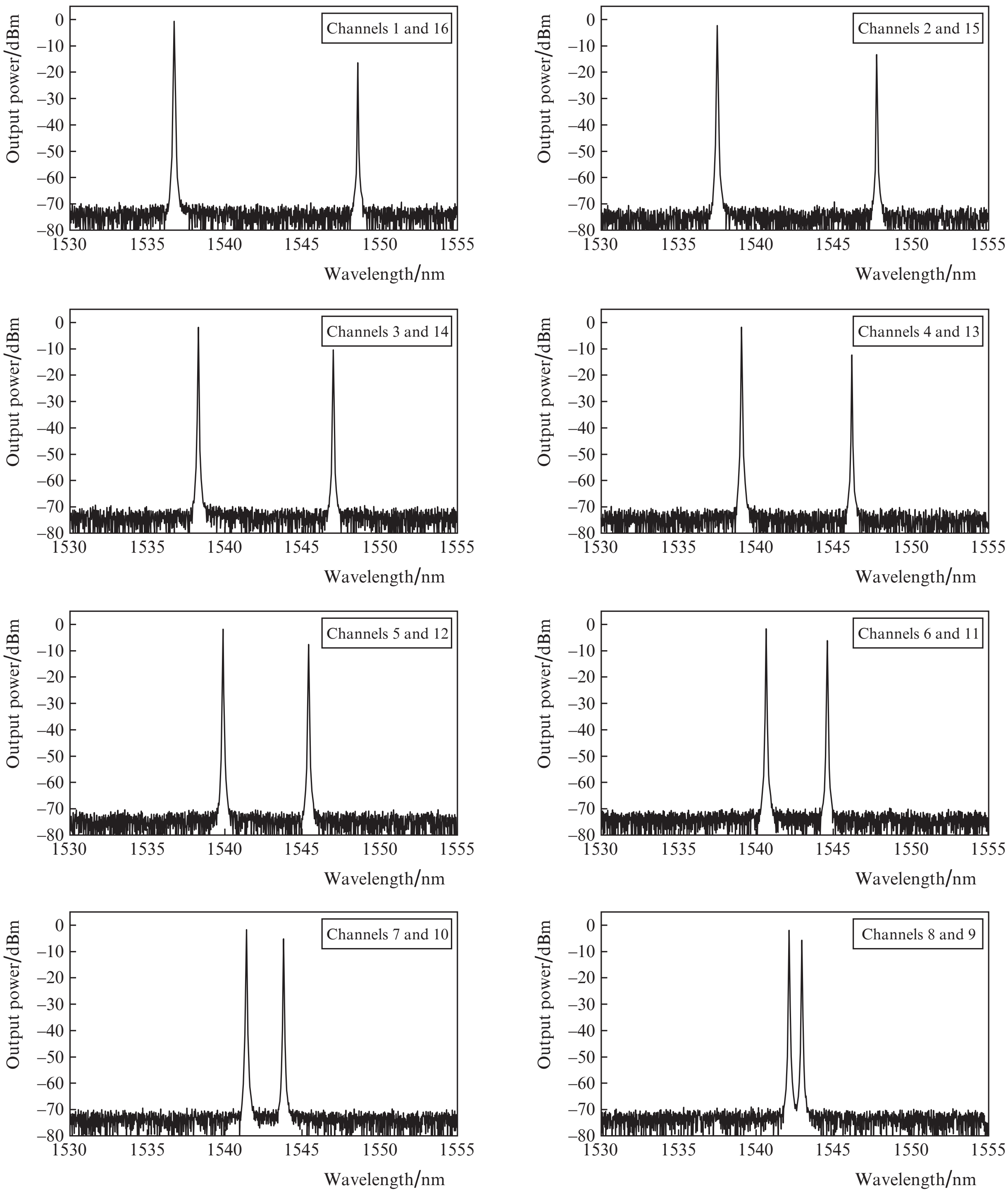

Figure 3. DWFL output from the ring cavity before the input to the booster amplifier.

overcome by balancing the dual wavelength output after the ring cavity. The VC losses can be adjusted such that the wavelength which experiences the higher gain at the booster amplifier will be reduced by introducing higher cavity losses before input into the second amplifier. The imbalanced output power of the ring cavity DWFL (see Fig. 3) is compensated by the wavelength dependent gain from the booster amplifier and implements a balanced HP-DWTFL (see Fig. 4).

Figure 4 shows the tuning range of the HP-DWTFL with Fig. 4a demonstrating the widest tuning range (12 nm, channels 1 and 16) that leads to lasing at wavelengths 1536.7 nm and 1548.6 nm, respectively. The narrowest tuning range of about 0.8 nm is contributed from channels 8 and 9 at wavelengths 1542.2 nm and 1543.0 nm, respectively (see Fig. 4h). The limitation of the tuning range which is only 12 nm can be improved by using an AWG with a higher number of channels that will expand the tuning range to a larger value. On the other hand, the narrowest tuning range can be improved by using a lower interchannel spacing of 25 GHz that leads to 0.2 nm spacing.

The high-power fibre laser produced using the proposed setup, however, leads to the emergence of the FWM effect

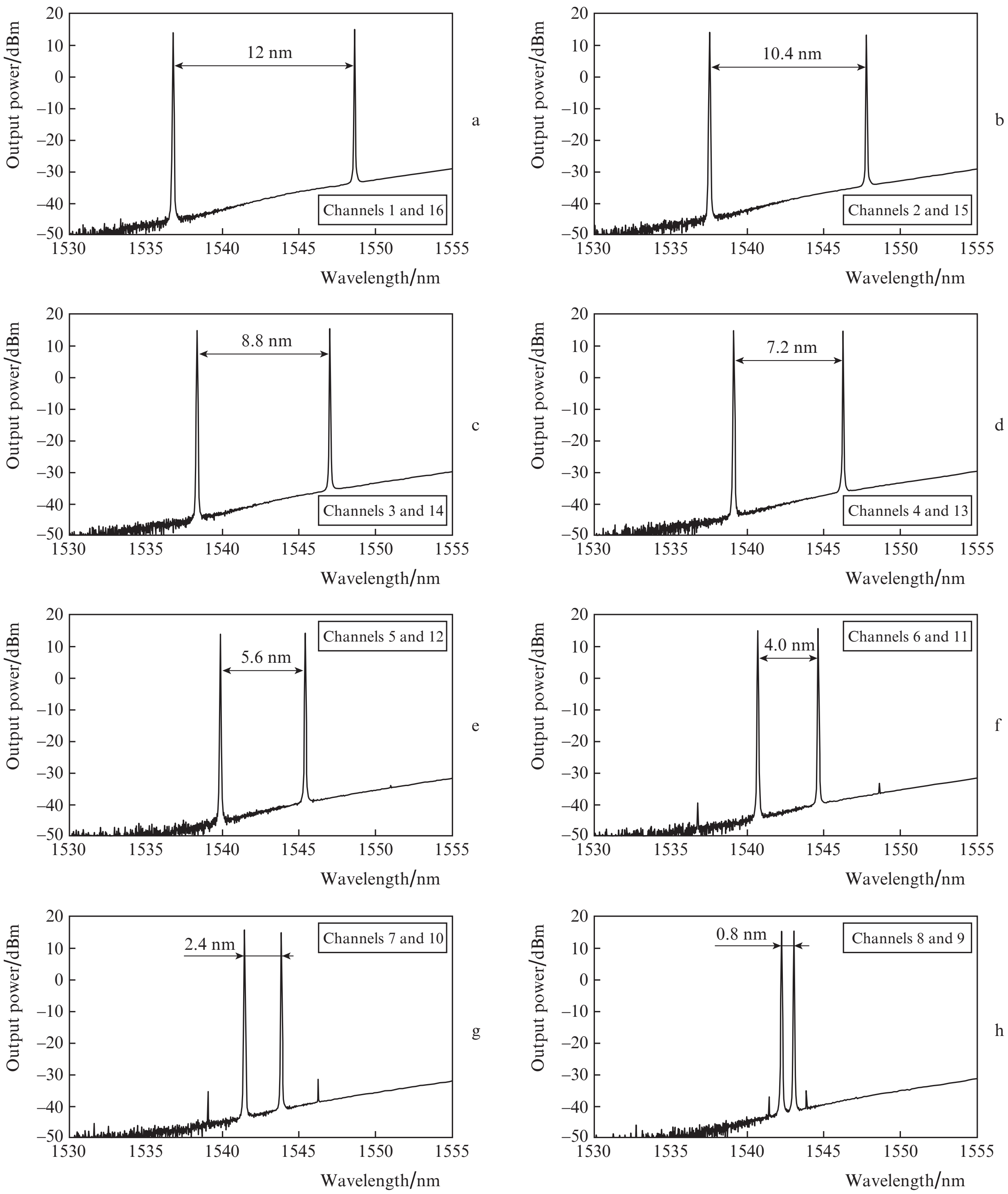

Figure 4. HP-DWTFL tuning range.

inside the booster amplifier which is caused by the high intensity of the electric field. This FWM effect starts from channels 6 and 11 (Fig. 4f) to channels 8 and 9 (Fig. 4h) with the mode offset for each dual-wavelength pair having the same spacings as that between the components of the pair. The effect of this FWM becomes greater as the spacing of the DWTFL gets narrower. This will result in a lower SMSR value. To overcome this, polarisation controllers should be inserted to optimise the output powers of the dual-wavelength and at the same time to reduce the peak power of the FWM outputs. This will improve the SMSR value.

Figure 5 shows the optimised output power of the HP-DWTFL that has been taken in pairs from channel 1 (1536.74 nm) and channel 16 (1548.6 nm), to channels 8 (1542.3 nm) and 9 (1543.1 nm). The average value of the output power is around 15 dBm with the highest output power coming from channel 11 (1544.62 nm) and the lowest from channel 15 (1547.8 nm) with 13.11-dBm output power. One can see that the output wavelength has been distributed evenly with 0.8-nm separation of two neighbouring channels. The output power of this HP-DWTFL is quite flat with peak-to-peak variations of ±1.315 dBm. The advantage of this setup is that it provides a

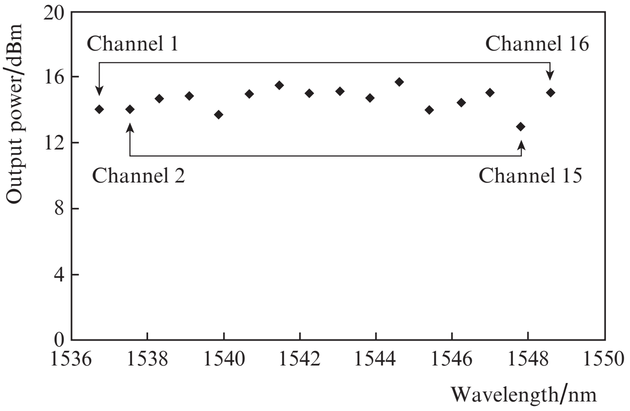

Figure 5. Optimised output powers of paired channels: 1 and 16, 2 and 15, 3 and 14, etc. with ±1.315-dBm output power variations.

rapid change in dual-wavelength outputs with different spacing using the fast response optical switch OS1 and OS2. However, for stable and flat output, the optical variable coupler has to be carefully adjusted and controlled to ensure a balanced output. The lower output power of channels 5 and 15 could be due to a higher connection loss at the AWG ports or the optical switch ports. This problem can be prevented by proper cleaning of the pigtails of the AWG and also those of the input ports to the optical switches.

Figure 6 shows the SMSR of the HP-DWTFL having the average value of 52.55 dB with a maximum difference of 12.4 dB indicating the stability of the proposed setup which is higher than that of a typical SMSR for fibre laser with the 40-dB SMSR [19]. This is an important parameter because the large noise level leads to an unstable fibre laser. The highest SMSR value is shown by channel 1 with a 58.77-dB SMSR, and the smallest comes from channel 10 with a 46.38-dB SMSR. The maximum difference is 12.4 dB, which is quite high, and is due to the ASE level difference of the gain medium with a higher gain at shorter wavelengths.

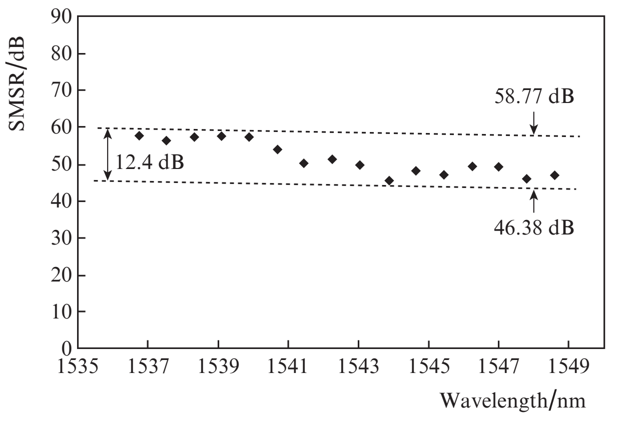

Figure 6. Spectral dependence of the SMSR of the DWFL.

Figure 7 presents the HP-DWTFL stability within an hour of operation. The graphs show that the HP-DWTFL is stable with only small changes in the output power. However, it can be seen that the stability of channels 1 and 16 is better than that of channels 8 and 9. This is due to the higher stability of the HP-DWFL at longer wavelength separation where the effect of mode competition is less as compared to at shorter wavelength separation. This problem, however, can be overcome by a proper control of the VC to provide the required cavity loss.

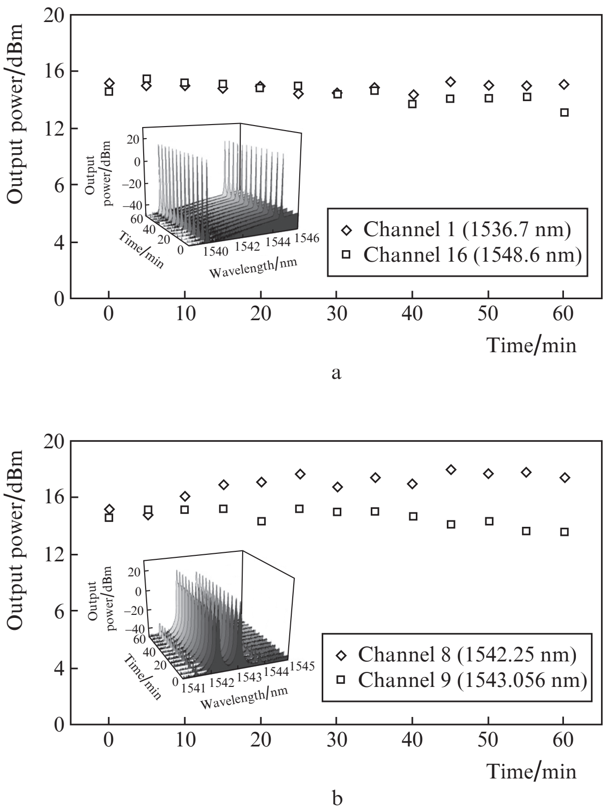

Figure 7. Temporal stability of the HP-DWTFL: channels 1 and 16 (a) and channels 8 and 9 (b).

4. Conclusions

We have constructed a HP-DWTFL operating in the C-band region (from 1536.7 nm to 1548.6 nm) by using a seeding signal and booster amplifier configuration with the normal 5- and 11-m-long Metrogain EDFs as the gain media. With the advantage of using the 1×16-channel AWG, this setup is capable of generating 16 different wavelengths to provide eight different spacing tunings of HP-DWTFL with the smallest spacing of 0.8 nm and the widest spacing of 12 nm. With an average output power of 15 dBm and SMSR of 52.55 dB, the setup is capable of producing a stable and tunable high power dual-wavelength fibre laser as can be seen from the good stability performance over an hour of operation .

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