

850 nm centered wavelength-swept laser based on a wavelength selection galvo filter

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A wavelength-swept laser is constructed using a free space external cavity configuration coupled with a fiber-based ring cavity at the 850 nm region. The external cavity filter employs a galvo-mirror scanner with a diffraction grating for wavelength selection. The filter is connected to a ring cavity through an optical circulator. The ring cavity contains a broadband semiconductor optical amplifier with a high optical output. The performance of this laser is demonstrated with broad bandwidths and narrow linewidths. The 3 dB linewidth and the bandwidth of this source are 0.05 nm (~ 20 GHz) and 48 nm, respectively. The maximum output power is 26 mW at 160 mA current.

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The function of a wavelength-swept laser is to generate light with discrete wavelengths by filtering the broadband light source. With the development of technology, the applications of a wavelength-swept laser have been extended to biomedical imaging such as spectroscopy, microscopy, and optical coherence tomography (OCT)^[1-3]. In OCT, the spectrum corresponding to the wavelength scanning range has been broadened according to its use in different applications. For eye imaging, the 850 nm range shows comparatively better retinal images due to less absorption of light^[3,4]. At 1300 nm, the biological samples have a relatively high optical penetration so more depth information can be acquired^[5,6]. Different types of gain media have been utilized to make wavelength-swept lasers in different regions; the 800 nm region with Ti:sapphire or semiconductor optical amplifiers (SOAs)^[4,7,8], the 1 μm region with SOA and Yb-doped fiber^[9], the 1.3 μm region with SOA^[10], the 1.5 μm region with Er-doped fibers^[11], and 2 μm Tm-doped fiber^[12] have been explored. Similarly, different kinds of filtering mechanisms have been investigated for wavelength sweeping that include a galvo scanner or rotating polygon mirror with a diffraction grating^[13], a fiber-based Fabry-Perot tunable filter (FFP-TF)^[9], an acousto-optic tunable filter (AOTF)^[7,11], and a fiber Bragg grating (FBG)^[8]. An SOA has the characteristics of broad gain bandwidth, short lifetime, and large emission cross section that enable good performance when coupled with a tuning filter.

In this Letter, a wavelength-swept laser is demonstrated for OCT applications. The wavelength-swept laser is based on a ring cavity containing an SOA (SOA-372, Superlum) and a wavelength selection filter. The wavelength filter consists of a galvo scanning mirror, which is a transmission-type diffraction grating and mirror. The wavelength selection is done by a rotating galvo scanner. The schematic diagram of the wavelength-swept laser is shown in Fig. 1. The components that formed the wavelength-swept

laser include an SOA gain medium, a polarization controller (PC), an optical isolator, an optical circulator, a galvo filter, and an optical coupler. All components are connected in a ring cavity configuration through an optical fiber. The isolator and circulator are connected in a ring cavity configuration to allow unidirectional propagation of infrared light from the SOA. The isolator prevents the back reflection of light to the SOA output terminal to avoid any damage. PCs are connected in the ring cavity to optimize the gain and to minimize the polarization dependency due to the diffraction grating and the SOA. The SOA has high power and a broad amplified spontaneous emission (ASE) profile suitable for a wavelength-swept laser. The SOA has a maximum gain at the 850 nm center wavelength with a 45 nm spectral bandwidth.

SOAs have a high gain, robustness, and quick response characteristics for wavelength amplification. Therefore, wavelength filtering based on an external cavity is used

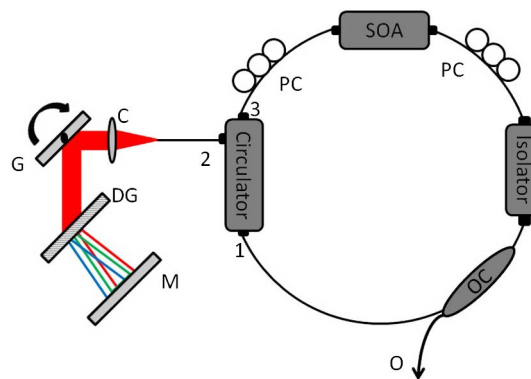


Fig. 1. Schematic diagram of a wavelength-swept laser based on a galvo mirror. C: Collimator, DG: diffraction grating, G: galvo scanner, M: mirror, O: output of wavelength-swept laser, OC: optical coupler.

to build a wavelength-swept laser. Wavelength selection in the external cavity configuration is achieved by a transmission-type diffraction grating (HD 1800 1/mm, Wasatch Photonics), galvo scanner (GVS001, Thorlabs), and mirror (PF10-03-P01, Thorlabs). The procedure for wavelength selection is described as follows. The light generated from the SOA contains a broad ASE spectrum with 9 mW power at 160 mA current. The SOA is connected to one arm of a 50:50 optical fiber coupler through an isolator. After passing through the isolator, the SOA power is divided by the optical coupler. At the coupler output, one arm is connected to terminal 1 of the optical circulator while the other arm is reserved for the final output of the wavelength-swept laser. The light with 50% of the total power exits from terminal 2 of the circulator and then is collimated by the collimator. After that it follows the path such that it is first incident on the galvo scanning mirror at a 45° angle and after reflection it passes through a transmission-type grating. The grating angularly diffracts light according to the wavelength at a blaze angle of 44°. Since the direction of grooves in the grating is vertical, the incident light on the grating is diffracted horizontally. Finally, the second mode of spectrally distributed light reflects back from a mirror placed at 2 cm distance. This reflected light follows the same return path and is coupled back to the circulator after passing through the grating, reflecting from the galvo scanner, and is finally incident on the collimator. Note that only the component of light that is normal to the mirror is coupled back to the fiber-based ring cavity. Hence, the movement of the galvo scanning mirror will allow each wavelength of light to be coupled back to the circulator to establish a sweeping output. The tuning wavelength of this galvo filter can be determined using the equation^[14]

$$\lambda_L = \frac{d}{m} (\sin \alpha + \sin \beta),$$

where λ_L is the tuning wavelength, d is the distance between grooves, and m is the diffraction mode. α and β are the incident and diffraction angles, respectively.

The galvo scanner has a 99.9% linearity with a repeatability of 15 μ rad. The input scale factor of this galvo is 0.8 V per degree with a maximum scan angle of $\pm 12.5^\circ$. The maximum operating frequency of this galvo at full scale is 250 Hz while at small scale it is 1 kHz. The input analog voltage signal range is ± 10 V.

The filtered light comes out from terminal 3 of the circulator. Since this terminal of the circulator is connected to the input terminal of the SOA, this spectrally distributed light from the filter feeds to the SOA. This filtered light is amplified by the gain medium of the SOA. As a result, the output power corresponding to the respective wavelength increases, which results in a high power optical output from the SOA.

Finally, the sweeping output as a function of the galvo scanner frequency can be obtained from the output terminal of the coupler. The output has a narrow spectral

linewidth throughout the spectrum. The ring cavity length of the wavelength-swept laser is around 2 m and the free space external cavity length is around 8 cm. Figure 2(a) shows the timing sequence of the wavelength-swept laser, with the swept laser output in red and the trigger in black. The laser output is shown with an arbitrary offset for visual guidance by increasing the gain of the photodetector. The trigger has a 10% duty cycle with 1 Hz frequency. The corresponding two sweeps appear as a result of the galvo filter, which operates with a triangular input signal. With customized hardware the sweep cycle can be adjusted according to the requirement of the optical system. In the current timing diagram the wider sweep corresponds to a 900 ms

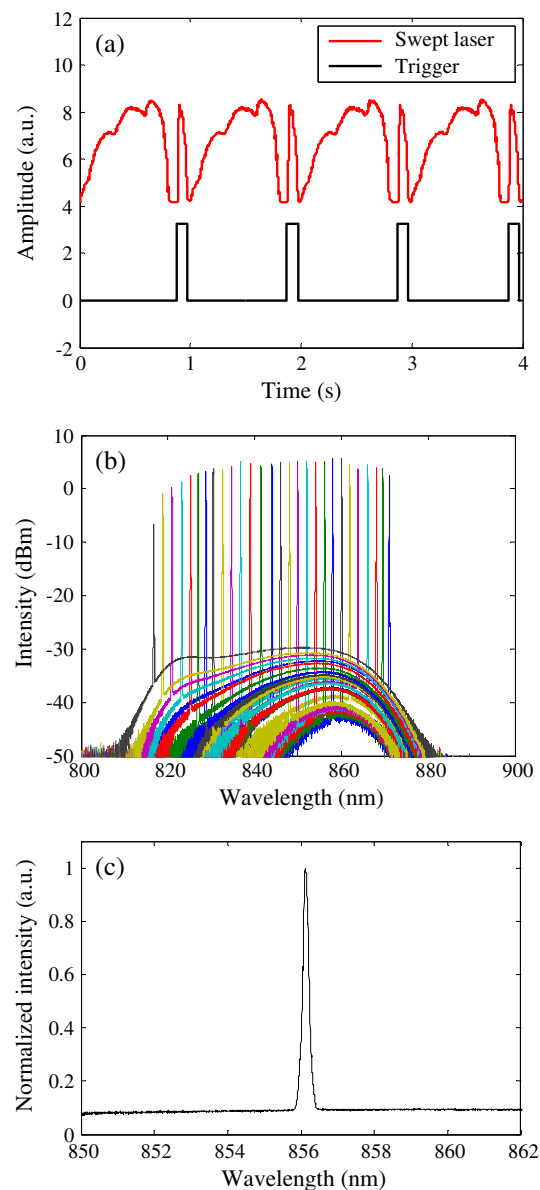


Fig. 2. (a) Timing diagram of the wavelength-swept laser (red) and 3.3 V trigger signal (black). (b) Amplified output of the wavelength-swept laser, each at 100 mV voltage increment to the galvo scanner. (c) Single linewidth plot at 856 nm center with a 0.05 nm (~ 20 GHz) 3 dB linewidth.

sweep duration while the other corresponds to a 100 ms duration. The intensity variation in the sweep output is due to the polarization dependency of the fiber and grating. This variation can be controlled by proper adjustment of the PC attached in the fiber ring cavity.

Figure 2(b) shows the output filtered wavelength at different input voltages applied to the galvo scanner. At discrete input voltage levels the corresponding wavelength will filter out from the ASE and feed back to SOA. The filtered output from the wavelength filter is amplified by the SOA and, as a result, a superposition of the ASE at a selected wavelength is obtained at the output of the source. The whole spectrum of the SOA is covered by applying a continuous input signal. The output power of the wavelength-swept laser is a function of the input driving current and the optical input from the filter to the SOA. The maximum output power of the wavelength-swept laser can be adjusted by controlling the current. The normal operating temperature of this wavelength-swept laser is 25°C and the driving current to the SOA is 160 mA. This spectrum is obtained at the increment of the 100 mV input signal to the galvo scanner, which results in approximately a 2 nm spectral shift.

Figure 2(c) shows the zoomed linewidth profile with a center wavelength of 856 nm. The spectrum of the wavelength-swept laser is obtained using an optical spectrum analyzer (AQ6370B, Yokogawa) with parameters of sensitivity and resolution selected as normal and 0.01 nm, respectively. The 3 dB linewidth of 0.05 nm is obtained as can be seen from the graph. The linewidth in terms of frequency can be calculated using the following equation:

$$\Delta\nu = \frac{c_o}{\lambda_L^2} \Delta\lambda.$$

Table 1 shows the maximum output power and bandwidth at three different values of the forward input current to the SOA. The 3 dB bandwidths of the wavelength-swept laser are 45, 46, and 48 nm at input currents of 140, 150, and 160 mA, respectively.

The relationship between the applied voltage signal to the galvo scanner and the filtered output is almost linear with a positive slope, as shown in Fig. 3. This graph indicates the sweep output from lower wavelengths to higher wavelengths, with increments of voltage. There is some nonlinearity due to the angular diffraction of the grating

Table 1. Peak Output Power at Different Driving Currents

Serial No.	Input Current (mA)	Bandwidth (nm)	Output Power (mW)
1	140	45	19
2	150	46	22
3	160	48	26

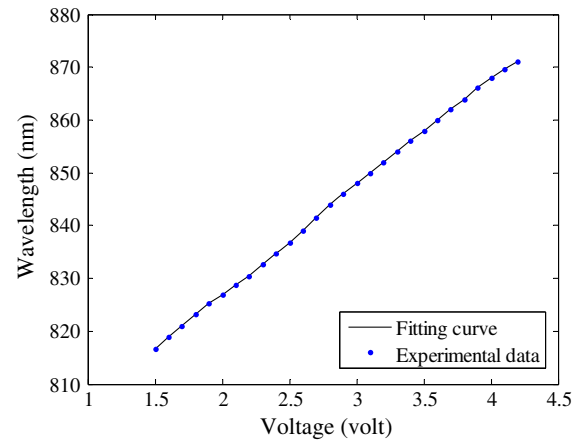


Fig. 3. Relation between input voltage and galvo scanning mirror and corresponding emitted spectrum as shown in Fig. 2(b).

and the polarization effect due to the fiber-based ring cavity, which can affect the sensitivity of the imaging system. By incorporating k-linearization^[15-17] this problem can be compensated. Using this graph, the desired output wavelength can be selected with a simple application of the corresponding voltage level to the galvo scanner filter. The following equation gives the specific wavelength at the desired input voltage, with a correlation of 0.9994,

$$\lambda_L = -0.2283v^2 + 21.804v + 784.3,$$

where, λ_L represents the wavelength and v is the input voltage.

The continuous swept profile can be obtained by applying the triangular input voltage to the galvo scanner. The sweep frequency of up to 1 kHz can be achieved with the current configuration. The maximum side mode suppression ratio of this wavelength-swept laser is 45 dB, with sufficient power to use in an OCT system. The spectrum of the wavelength-swept laser ranges from 815 nm to 870 nm, with 10 dB bandwidth.

In conclusion, we propose a simple and effective wavelength-swept laser based on a free space galvo-scanner filter. The wavelength sweeping is achieved by a transmission-type diffraction grating and a galvo scanner. Since the wavelength selection by the diffraction grating and galvo mirror are separated, the angle alignment stability is improved. Due to the precise alignment of the external cavity filter, the filtered wavelength is coupled back to the fiber-based ring cavity. The output of the wavelength-swept laser can be tuned up to 55 nm, with a 10 dB fall off. The achieved overall 3 dB bandwidth of this source is 48 nm at 160 mA current, with the linewidth of 0.05 nm. For this laser, at the input current of 160 mA, the maximum power of 26 mW is achieved. Our proposed wavelength-swept laser has advantages of narrow linewidth, easy tuning, and adjustable high output power. The narrow linewidth and broad bandwidth of this source can improve the imaging depth and axial resolution in an OCT system. As compared to the previously reported wavelength-swept laser, which has 0.085 nm linewidth

and 38 nm bandwidth^[18], this source can perform well. It can also be used with a full-field OCT system for retina imaging^[19], where a very high sweep rate is not required.

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