Simple fiber-optic source for optical coherence tomography

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A high-power fiber-based spontaneous emission light source with a tunable filter can be ideal for Fourier-domain optical coherence tomography systems used in biomedical applications.

Light sources for most medical technologies use semiconductor diodes or lasers, whether solid-state or gas-based, sometimes coupled to a fiber to deliver light. Fiber-optic sources have yet to become widely accepted. However, a doped optical fiber can provide a highly efficient source with broad bandwidth and high average power, two characteristics with many biomedical uses. In this regard, Fourier domain optical coherence tomography (FD-OCT) represents a new and especially promising system.

Two of the most widely used fiber-optic sources are based on erbium-doped or ytterbium-doped fibers. The former are primarily used for optical communication applications in a 1550nm window, but the long center wavelength makes them unsuitable for OCT applications. More appropriate for work with FD-OCT are Yb-doped fibers. Pumped by a diode laser, they can produce broadband light centered around 1060nm with the bandwidth in excess of 50nm. The source is simple to build using standard, commercially available components and can readily provide several watts of continuous wave power.

In general, Yb-doped fibers provide an extremely broad band with high spectral density in the near-IR, making them an ideal source for FD-OCT.

There are essentially two ways to build an FD-OCT system. The standard method uses a broadband source and a spectrometer, while an alternative employs a wavelength-swept source and single detector. For the optical source, the main technical challenges concern sufficient spectral density and, in the case of a tunable laser-based system, fast wavelength sweeping speed for high-speed image acquisition. Ideally, one would like to obtain an average of several hundred microwatts of power at each spectral band, while mindful of phototoxicity that, in general, limits tissue-illuminating power to several milliwatts.

Typical superluminescent light-emitting diode (SLED) sources only provide average power on the order of a few milliwatts. This means that if .05nm spectral resolution is required for an FD-OCT system, the maximum spectral power will be only a few microwatts. Because actual signal power at the detector/charge-coupled device (CCD) array is at most ~30dB lower than the incident light, a lengthy integration is required to obtain reasonable signal-to-noise ratio. Thus, a low-power SLED source is not ideal for a FD-OCT system.

Wavelength-swept laser sources are under investigation and have been used to obtain high spectral density. However, the gain dynamics and long photon lifetime of the doped-fiber-based laser systems make it difficult to obtain rapid sweep speed. In addition, amplitude and phase noise can affect image quality. A simpler and cheaper alternative to the tunable laser is a wavelength-swept source based on a combination of a high-power Yb-doped-fiber-amplified spontaneous emission (ASE) light source and a voltage-controlled tunable optical filter (see Figure 1).

A typical tunable filter based on a scanning Fabry-Perot filter can be tuned continuously over 50–100nm bandwidth at a rate up to tens of kilohertz. The ASE source is based on a doubled-clad Yb-doped fiber pumped with a high-power multimode diode bar. A fixed spectral-shaping filter at the output of the source can be used to obtain a desired configuration. The maximum output power of the ASE source that we built is 5W. The more conventional Yb-doped fiber pumped (forward and backward) with single-mode diode bars can provide approximately 0.5W. Figure 2 shows the time-averaged output spectrum of the source. We attenuated the power before sending it to an optical spectrum analyzer.
This scheme works because Yb-doped-fiber ASE sources can output high average power and FD-OCT systems do not require high spectral resolution less than 0.01nm. One drawback is that this system is highly inefficient inasmuch as more than 99% of energy is lost. However, power and bandwidth are relatively inexpensive. This system may in consequence prove cheaper, simpler, and more robust than the conventional sources for FD-OCT.

Figure 2. Time-averaged spectrum of the Yb-doped-fiber-based ASE source. The output was attenuated for the optical spectrum analyzer.

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References

3. Values for phototoxicity depend on tissue type and beam focus, and one should refer to ISO 15004-2 for additional information.