An **Alternative to LEDs** for Full-Field Imaging

A broadband fiber amplified spontaneous emission light source delivers the brightness and low spatial and temporal coherence required for optical coherence tomography and ranging applications.

BY BRANDON REDDING, U.S. NAVAL RESEARCH LAB; PEYMAN AHMADI, NUFERN INC.; and HUI CAO, YALE UNIVERSITY

For some applications, the defining attributes of traditional lasers — high spatial and temporal coherence — can have an adverse effect. High spatial coherence introduces artifacts such as speckle in imaging, which degrades the image. As a result, low-spatial coherence sources such as thermal sources or LEDs are still used in most full-field imaging systems, despite their limited brightness. Low temporal coherence is also desirable in optical coherence tomography (OCT) or frequency resolved lidar, since it provides depth information or ranging.

While thermal sources and LEDs have both the low spatial and low temporal coherence required for applications, they do not provide the laser-level brightness needed for high-speed parallel imaging systems or imaging with the intense optical scattering common for biomedical imaging.

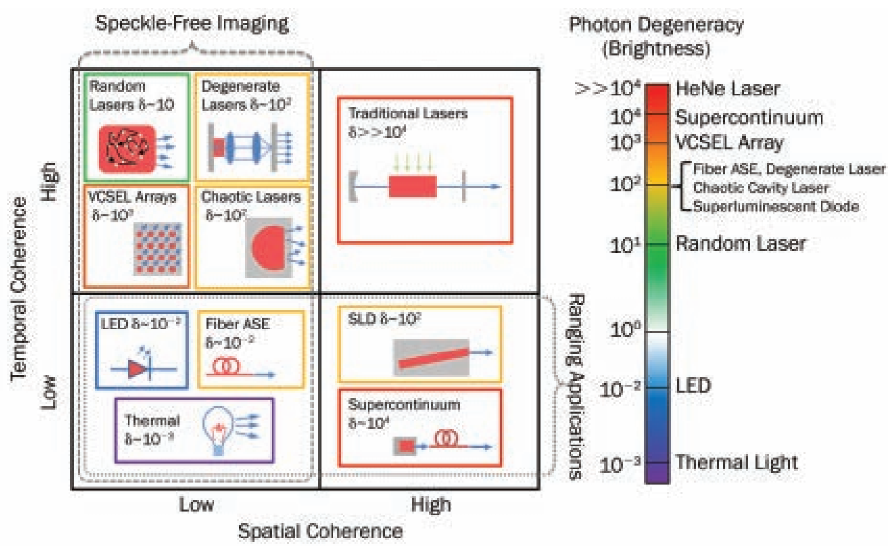

Figure 1. Light sources are categorized in terms of their spatial coherence, temporal coherence and power per mode. Low spatial coherence sources enable speckle-free imaging while low temporal coherence sources enable ranging applications. The recently developed fiber ASE (amplified spontaneous emission) source uniquely combines low spatial and low temporal coherence while maintaining high photon degeneracy.

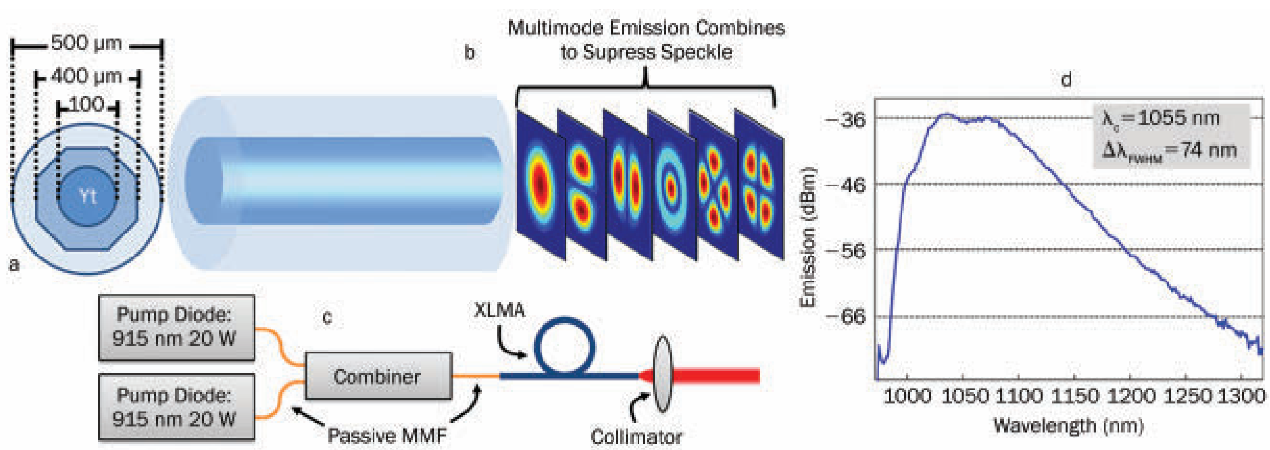

Figure 2. Cross section of the Yb-doped XLMA fiber **(a)**. The fiber consists of a 100-μm-diameter, Yb-doped gain core with NA=0.1 surrounded by an octagonal 400-μm pump core and a 480-μm outer cladding. The multimode gain core provides amplified spontaneous emission (ASE) in many spatial modes simultaneously **(b)**. Schematic of the fiber ASE source **(c)**. The emission spectrum from the fiber ASE source is centered at 1055 nm with a 3-dB bandwidth of 74 nm **(d)**.

 All images courtesy of Nufern.

Brightness can be quantified by a parameter called photon degeneracy, which is defined as the number of photons per coherence volume and is equivalent to the spectral radiance or power per mode of a light source. In a laser, the photon degeneracy is usually much greater than unity; for example, a typical HeNe laser has a photon degeneracy of about 10^9. In contrast, traditional low coherence sources such as thermal sources and LEDs have a degeneracy of less than 1. In recent years a number of light sources have been developed that maintain high photon degeneracy, while providing either low spatial coherence or low temporal coherence — but not both.

A research team from Yale University and Nufern Inc. recently categorized different light sources in terms of their spatial coherence, temporal coherence and photon degeneracy (δ) (Figure 1). Traditional lasers combine both high spatial and high temporal coherence along with high photon degeneracy (which is color-coded in the figure). While this combination has made lasers a powerful tool for a wide variety of applications, the high spatial coherence has limited the adoption of lasers in parallel imaging and projection applications. The high temporal coherence limits use in ranging applications, including OCT or frequency resolved lidar. Superluminescent diodes (SLDs) and supercontinuum light sources have low temporal coherence, enabling ranging applications, while maintaining high spatial coherence and high brightness. These sources have been widely used in OCT, but are poorly suited for full-field imaging due to their high spatial coherence.

Recently, several multimode lasers that combine low spatial coherence with high brightness required for speckle-free imaging have been developed, including dye-based random lasers[1], powder-based random Raman lasers[2], solid-state degenerate lasers[3], semiconductor-based chaotic cavity lasers[4], and semiconductor-based large-area vertical-cavity surface-emitting lasers (VCSELs)[5] and VCSEL arrays[6]. While these light sources enable speckle-free imaging with a high brightness source, they maintain relatively high temporal coherence and are not suitable for ranging applications.

The Yale/Nufern team recently developed a fiber amplified spontaneous emission (ASE) source that combines low spatial coherence with low temporal coherence, while maintaining high power per mode[7]. Although thermal sources and LEDs also combine these characteristics, the fiber ASE sources provide orders of magnitude higher brightness. It is also the first demonstration of a high-brightness, speckle-free fiber-based light source that provides many of the same advantages inherent to traditional fiber lasers, such as excellent beam quality, emission directionality and robustness.

To achieve low spatial and low temporal coherence, the researchers needed a fiber source that provided emission in a large number of spatial modes over a wide spectral band. To accomplish this, they

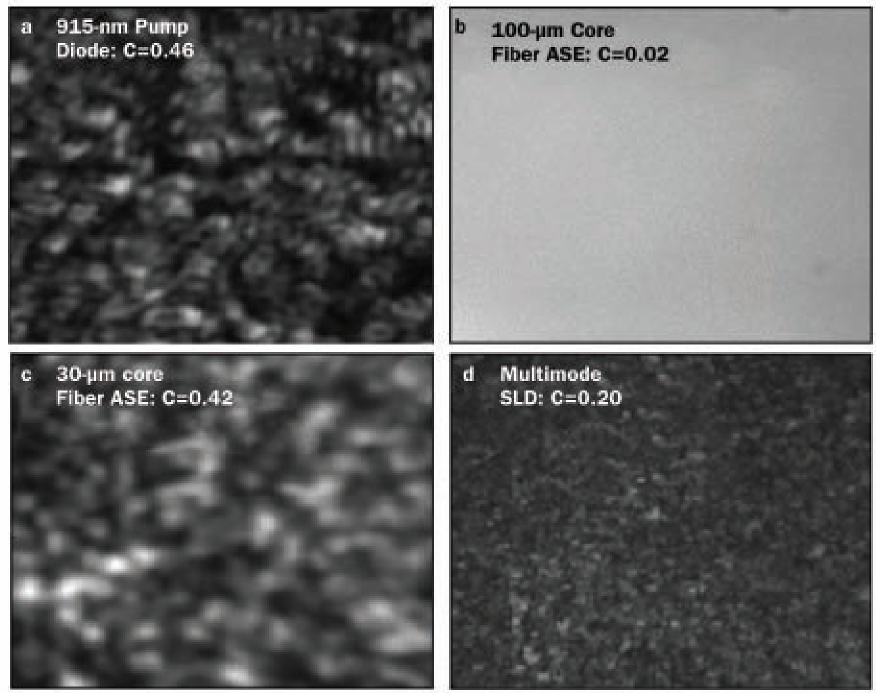

Figure 3. Emission from the pump diode **(a)** and the 100-µm core fiber ASE source **(b)** is collimated onto a ground glass diffuser and the transmitted light is recorded on a camera. The spatially coherent laser light from the pump diode produces a speckle pattern with contrast of about 0.46, whereas the low spatial coherence fiber ASE source efficiently suppresses speckle, resulting in uniform illumination on the camera with a contrast of about 0.02. A 30-µm core fiber ASE source **(c)** and a multimode SLD **(d)** were also tested; however, neither source supported enough modes to effectively suppress speckle formation.

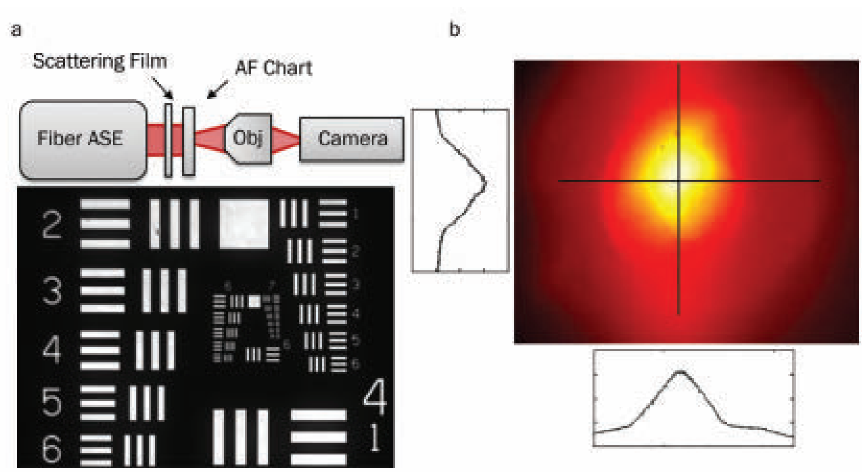

Figure 4. A speckle-free image of a resolution chart illuminated in transmission through a scattering film with the fiber ASE source **(a)**. The spatial profile of the collimated fiber ASE output beam **(b)**.

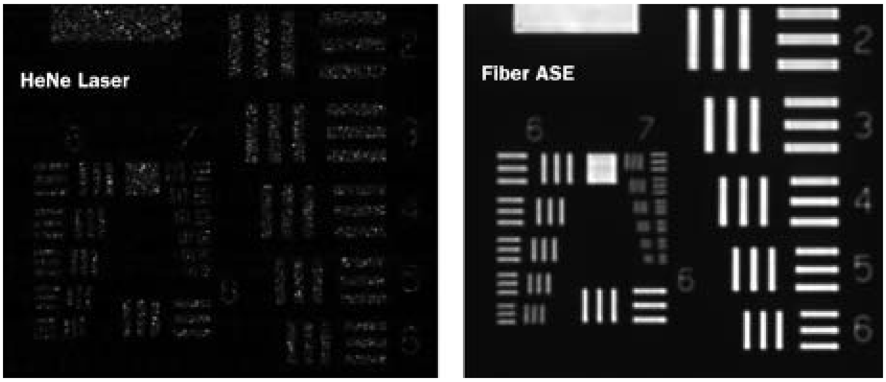

Figure 5. A resolution chart was imaged under illumination from a standard HeNe laser and the fiber ASE source. The fiber ASE source suppresses the formation of speckle, which has historically precluded imaging with laser and ASE-based light sources.

used a recently developed fiber with an extra-large mode area (XLMA) gain core. The XLMA fiber used in the initial demonstration had a 100-µm-diameter, Yb-doped gain core surrounded by a 400-µm diameter pump core, and a 480-µm diameter outer cladding (Nufern XLMA-YTF-95/400/480) (Figure 2a). The large gain core supported about 360 spatial modes providing the potential for low spatial coherence. To achieve broadband emission with low temporal coherence, the spontaneous emission is amplified in the fiber and lasing is avoided by minimizing feedback from the end facet of the fiber with an angled cleave.

The fiber ASE source provided emission in many spatial modes simultaneously (Figure 2b); additionally the source emission was quite broadband, indicative of low temporal coherence (Figure 2d).

The light source produced 270 mW of CW emission with a center wavelength of 1055 nm and a 3-dB bandwidth of 74 nm. While higher output power can be expected in the future, this first-generation fiber ASE source already provides about 4 mW/nm, comparable to commercially available supercontinuum sources[8].

Suppressing speckle formation

The researchers then assessed the fiber ASE source's ability to suppress speckle formation. To do this, they collimated the emission onto a ground glass diffuser and recorded images of the transmitted light with a camera. As a reference, they first measured the intensity pattern formed by laser light from one of the 915-nm pump diodes, which produced a high-contrast speckle pattern (Figure 3a). Repeating the experiment with the fiber ASE source produced a uniform image (Figure 3b).

To quantify the speckle suppression, they calculated the speckle contrast of the two images. The pump diodes produced a contrast of about 0.46 (less than unity due to the use of multiple pump diodes), whereas the fiber ASE source produced a speckle contrast of only about 0.02.

The researchers also compared the speckle formation using two additional ASE sources: a fiber ASE source based on a 30-µm diameter gain core and a commercially available semiconductor-based multimode super luminescent diode (Superlum M-381) (Figure 3c, d). The 30-µm diameter fiber ASE source produced relatively broadband emission with a 3-dB bandwidth of about 20 nm centered at about 1055 nm; however, the emission still produced speckle with a contrast of about 0.42. The multimode SLD (which also operates based on ASE) provided about 150 mW of power at $\lambda=800$ nm with a 3-dB bandwidth of 40 nm. Nonetheless, the SLD also produced speckle with contrast of about 0.2. Thus, the XLMA fiber ASE source was the only ASE source that suppressed speckle to acceptable levels for full-field imaging applications.

Initially, it was surprising to find that the multimode fiber ASE source supported such a large number of spatial modes, whereas the ASE produced by a semiconductor-based multimode SLD maintained relatively high spatial coherence and produced high-contrast speckle. In addition, previous studies found that mode competition in multimode Fabry-Perot lasers limited lasing to only a few modes, even in waveguides supporting several hundred transverse spatial modes[9].

The researchers suggested two factors that could enable the fiber ASE source to support a large number of modes. First, the SLD and the multimode Fabry-Perot laser both used semiconductor quantum wells as gain materials, which allow for efficient carrier diffusion. This has the effect of increasing the mode competition[10]. In contrast to a quantum well, the Yb dopants in the XLMA fiber are spatially localized, leading to spatial hole burning, which can reduce the effects of mode competition. Second, the fiber bending and imperfections in the XLMA fiber can introduce mode coupling such that a mode that initially experiences strong gain may couple into a mode with lower gain, thereby equalizing the gain experienced by different modes over the length of the fiber. The reduction of mode-dependent gain in the multimode fiber favors multimode operation[11]. Thus, the fiber medium may be particularly well-suited to the development of highly multimode ASE appropriate for speckle-free imaging.

The researchers then used the fiber ASE source to illuminate a U.S. Air Force resolution test chart, which was imaged in transmission mode. A speckle-free, full-field image was obtained (Figure 4a). In addition to providing the low spatial coherence needed for imaging, the low temporal coherence (broad emission spectrum) makes the fiber ASE source a good candidate for ranging applications such as OCT. For example, the 74-nm emission bandwidth would provide an axial resolution of 6.6 µm in OCT. The fiber ASE source also exhibits high directionality, with a divergence angle of less than 6°. Despite the presence of many spatial modes, the spatial profile of the output beam from the fiber ASE source is smooth and stable — ideal for illumination in imaging applications, as confirmed by the image of the collimated beam (Figure 4b).

In addition to producing speckle-free illumination like a thermal source or LED, the fiber ASE source also provides much higher brightness, useful for high-speed imaging or imaging through scattering samples. As a quantitative comparison, the team estimated the photon degeneracy of the fiber ASE source to be about 10^2, as compared with LEDs and thermal sources, which are limited to a photon degeneracy well below unity. The fiber ASE source also provides a comparable level of photon degeneracy to recently developed low-spatial coherence lasers, as shown in Figure 1.

The fiber ASE source uniquely combines high power per mode with both low spatial and low temporal coherence. The ASE source produces 270 mW of CW emission with a 74-nm 3-dB bandwidth centered at $\lambda = 1055$ nm. Highly multimode emission, combined with spectral compounding, enables speckle-free imaging while the broad emission spectrum also makes it an attractive light source for ranging applications. The researchers expect that increasing the size of the gain core could enable emission in more spatial modes while also providing the potential for higher power. As such, the XLMA-based fiber ASE source could enable new applications in high-speed parallel imaging, projection and ranging.

References

1. B. Redding et al. (2012). Speckle-free laser imaging using random laser illumination. *Nat Photonics*, Vol. 6, pp. 355-359.
2. B.H. Hokr et al. (2016). A narrow-band speckle-free light source via random Raman lasing, *J Mod Opt*, Vol. 63, pp. 46-49.
3. M. Nixon et al. (2013). Efficient method for controlling the spatial coherence of a laser. *Opt Lett*, Vol. 38, pp. 3858-3861.
4. B. Redding et al. (2015). Low spatial coherence electrically pumped semiconductor laser for speckle-free full-field imaging. *Proc Natl Acad Sci*, Vol. 112, p. 1304.
5. F. Riechertet al. (2008). Speckle characteristics of a broad-area VCSEL in the incoherent emission regime. *Opt Commun*, Vol. 281, pp. 4424-443.
6. J.-F. Seurin et al. (2009).K. D. Choquette and C. Lei, Eds. Progress in high-power high-efficiency VCSEL arrays. *Proc SPIE*, Vol. 7229, 722903, 1-11.
7. B. Redding et al. (2015). Low-spatial-coherence high-radiance broadband fiber source for speckle free imaging. *Opt Lett*, Vol. 40, p. 4607.
8. N. Savage (2009). Supercontinuum sources. *Nat Photon*, Vol. 3, pp. 114-115.
9. B. Redding et al. (2015). Low spatial coherence electrically pumped semiconductor laser for speckle-free full-field imaging. *Proc Natl Acad Sci*, Vol. 112, p. 1304.
10. J. Hao et al. (Elsevier, 2013). Effect of mode competition on photodarkening distribution of Yb-doped fiber laser. *Opt Commun*, Vol. 287, pp. 167-175
11. K. P. Ho and J. M. Kahn (2014). Linear propagation effects in mode-division multiplexing systems. *J Light Technol*, Vol. 32, pp. 614-628.
12. B. Redding et al. (2015). Low-spatial-coherence high-radiance broadband fiber source for speckle free imaging. *Opt Lett*, Vol. 40, p. 4607.

Meet the authors

Brandon Redding, Ph.D., joined Hui Cao's lab at Yale University in 2010 as a postdoctoral fellow, and is currently a research physicist at the U.S. Naval Research Lab.; email: redding.brandon@gmail.com. Peyman Ahmadi, Ph.D., joined Nufern Inc. in 2011 as a scientist and currently manages the industrial R&D group; email: pahmadi@nufern.com. Hui Cao, Ph.D., is a professor of Applied Physics and Physics at Yale University; email: hui.cao@yale.edu.