Superluminescent Diode Light Sources for OCT

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Contrary to laser diodes, the way of superluminescent diodes (SLDs) to their wide use in practice was much longer. There was always a certain scientific interest to “superluminescent” light output from laser diode structures slightly below threshold that might be considerably enhanced by “damping” of laser resonator (for example, by tilting of mesa structures) [1–3]. However, there was no considerable practical interest to such lightsources until it was proved that SLDs are the real “lightsources of choice” for fiber-optic gyroscopes [4]. Successful use of first SLDs in gyros in early 1980s, as well as some overestimated market demand for gyros, has considerably intensified SLD design efforts. This resulted in development of “first SLD generation” with gyro-rated power outputs, a few milliwatt in singlemode (or polarization maintain) fiber at 800–850nm and 1300–1550nm bands. Development of gyro-graded SLDs has also given some additional impetus to their usage as lightsources in other prospective sensing systems, such as Faraday-effect electric current sensors, distributed Bragg-grating sensor systems, and some others.

The “second wave” of interest to SLDs as lightsources came after successful demonstration of OCT technique and its advantages comparing with other probing techniques in medicine, as well as in some other applications [5]. OCT required development of much more powerful SLDs than those existed in earlier 1990s, particularly with output power of at least 10mW from SM fiber with still wide and flat optical spectrum. At the same time there appeared other new applications for such SLDs, for example, testing of fiberoptic telecom components (including WDM/DWDM). This additionally intensified design efforts.

As a result, SLDs are now lightsources of choice for a great number of different applications. While in some specific areas, like ultrahigh-resolution OCT, there are strong competitors to SLDs, namely femtosecond lasers/supercontinuum sources, for most of practical applications SLDs are now considered as the most attractive emitters due to their small size, easy use, and much smaller price compared to alternative lightsources.
Each application has its own specific requirements to SLD performance parameters, but OCT requirements are still the most hardly to meet. The main reason for this is the fact that high optical power, wide spectrum, and negligible parasitic spectral modulation must be realized simultaneously. From this point of view, OCT may be considered as “the main driving vehicle” for further improvement of SLD performance and for developing of new approaches to increase SLD power and to decrease coherence length. We will overview and discuss the main principles of developing powerful broadband SLDs and their performance parameters. Some important aspects of SLD use in practice will be discussed. We will also describe ultra-low-coherence lightsources based on combination of different SLD modules. Possibilities for further improvement of SLDs and SLD-based lightsources will be discussed as well.

9.1 Main Principles of SLD Operation and SLD Spectrum Broadening

The unique property of superluminescent diodes is the combination of laser-diode-like output power and brightness with broad LED-like optical spectrum. Such combination is allowed by high optical gain and wide gain spectrum in semiconductor laser materials.

In fact, any “ideal” SLD is optimized traveling wave laser diode amplifier with zero reflections from the ends of active channel. In every SLD two counterpropagating beams of amplified spontaneous emission are traveling along active region. For estimation of its output power, SLD may be described relatively well by simple model that does not take into account spectral effects and considers uniform distribution of carriers’ density in SLD active region [6,7]. Stationary distributions of photon densities in each direction, carrier density, and driving current density are described by well-known equations of traveling wave laser diode amplifier [6,7]:

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\begin{align*}
\frac{c}{d} \frac{dS^+}{dz} &= c(g - \alpha)S^+ + \beta \frac{N}{\tau_{sp}}, \\
-\frac{c}{d} \frac{dS^-}{dz} &= c(g - \alpha)S^- + \beta \frac{N}{\tau_{sp}}, \\
Q(z) &= N/\tau_{sp} + cg(S^+ + S^-),
\end{align*}
\]

where \(S^+\) and \(S^-\) are photon densities of forward and back propagated waves in active region, \(g\) is modal optical gain, \(\alpha\) is nonresonant optical losses of waveguided mode, \(\beta\) is fraction of spontaneous emission coupled into guided mode, \(N\) is carrier density, \(\tau_{sp}\) is spontaneous lifetime, \(Q\) is driving current density, \(c\) is the velocity of light.

Equations (9.1–9.3) may be solved analytically by assuming carrier density constant across the active region [6], that is good approximation in the