Superluminescent Diodes.
Short overview of device operation principles and performance parameters.

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Principles of SLD operation. SLD output power.

The unique property of superluminescent diodes (SLD) 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 in semiconductor laser materials and its wide optical spectrum.

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. In terms of output power, SLD performance 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. By using such a model and considering zero reflections from the ends of active channel, distribution of photon density inside SLD active region and SLD output power may be expressed as (see also Fig.1 for details):

$$S^{+}(z) = R_{sp}\frac{\exp[(g-\alpha)z]-1}{g-\alpha}/c \qquad ;(1)$$

$$S^{-}(z) = R_{sp}\frac{\exp[(g-\alpha)(L-z)]-1}{g-\alpha}/c \qquad ;(2)$$

$$P_{out}^{+}(L) = h\upsilon\,\Pi S^{+}(L) = h\upsilon\Pi\left(R_{sp}\frac{exp[(g-\alpha)L]-1}{g-\alpha}\right)/c \quad ,(3)$$

where $\boldsymbol{R_{sp}}$ – spontaneous emission rate into guided mode, $\boldsymbol{g}$ – modal gain, $\boldsymbol{\alpha}$ – non-resonant optical losses, $\boldsymbol{L}$ – length of active channel, Π – size of optical mode, $\boldsymbol{h}$ – Plank's constant, $\boldsymbol{\upsilon}$ – optical frequency, $\boldsymbol{c}$ – velocity of light. Light-current characteristics of SLD may be estimated by integrating the balance equation for carriers and photons:

$$G(z) = N/\tau_{sp} + cg(S^{+}(z) + S^{-}(z)) \quad ;(4)$$

(τ_{sp} is spontaneous lifetime) over z (z-axis is directed along active channel).

It is seen from (1 – 3) that SLD power depends exponentially on optical gain and linearly on spontaneous emission rate. Evidently, high value of modal gain is desired to obtain high output power. Let us discuss some numerical estimation for "typical" superluminscent diodes.

Fig. 1 shows simulated and typical light-current characteristic of 50 mW free-space/20 mW SM fiber output SLD of Superlum Diodes, type SLD-38-HP at 820 nm spectral band. Its design is optimized to get high output power. Fig. 1 also shows calculated distribution of photon density and current density (using eq. (4)) inside the active region at 180 mA SLD current and 30 mW free space power (about 10 mW SM fiber coupled power).

It is seen that net gain $\boldsymbol{G = exp((g-\alpha)L)}$ = 28 dB is realized at 180 mA and 30 dB gain is realized at 250 mA when SLD free space output power reaches 50 mW. Estimations also show that modal gain in SLD is ***at least*** two times higher than threshold modal gain in laser diodes. Both photon density and current density are distributed non-uniformly along the active region.

This specific, added by very high value of optical gain, results in some specific features of SLD as light emitters.

Fig.1. also shows the other example of simulated and "typical" performance of medium-power 820 nm SLD of Superlum Diodes, type SLD-38-MP. There is no need for very high net gain to get 5-7 mW SLD output, and this allows to optimize SLD design also by "price-to-performance" figure .

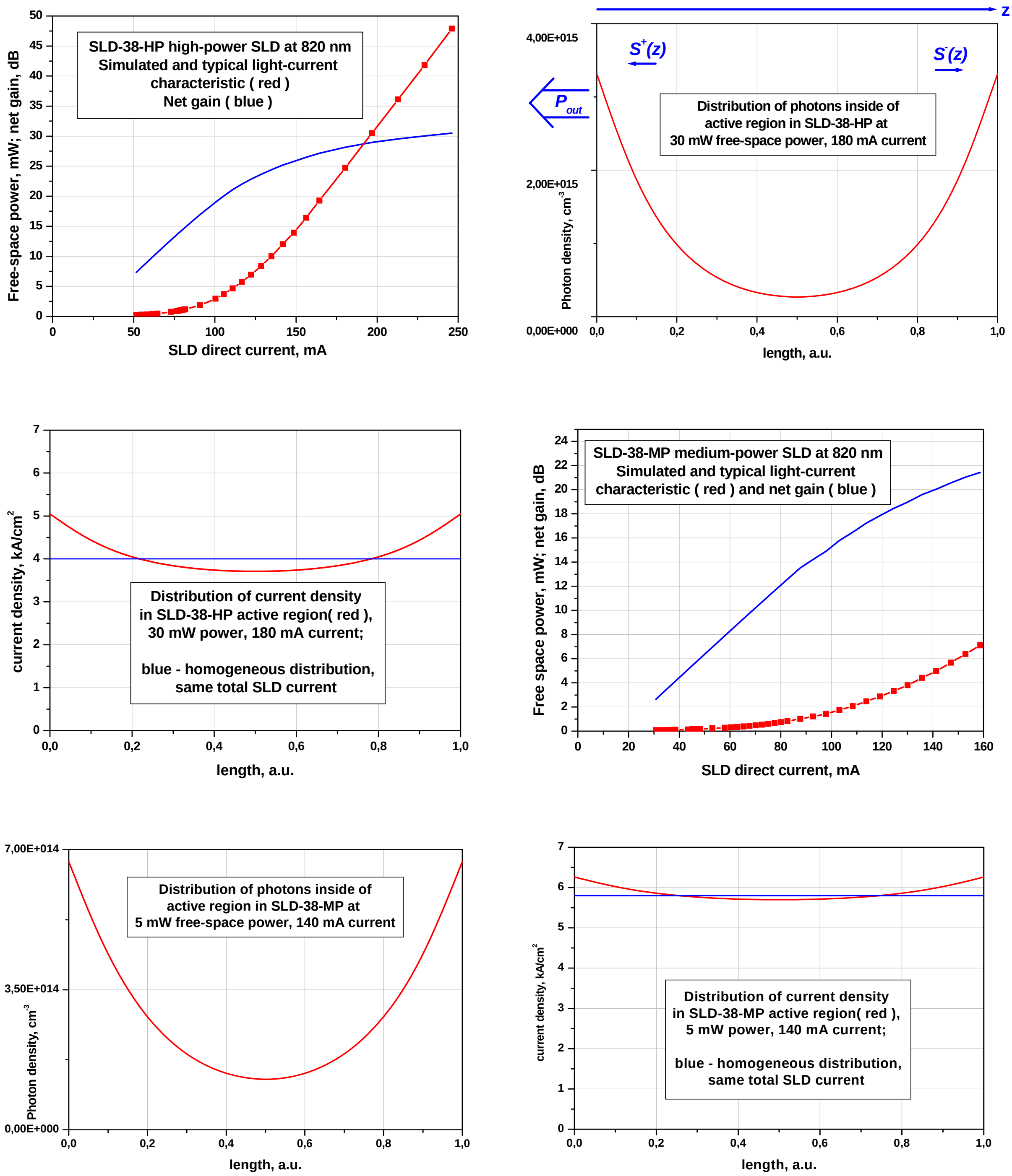


Fig. 1. Net gain, light-current characteristics and distribution of photon density and driving rate density in high-power SLD-38-HP and medium-power SLD-38-MP. Main differences of SLD with respect to laser diodes are: much higher gain, much higher current density and very much stronger non-uniformity of photons and driving current distribution inside the active region.

SLD spectrum and coherence

There is number of parameters describing SLD spectral properties, but the main of them (excluding, of course, central wavelength) are :

- Spectrum width, which is always expressed in terms of Full Width at Half Maximum (FWHM), spectrum width determines so-called coherence length;
- Residual spectral modulation, which characterizes parasitic Fabry-Perot modulation due to non-zero reflections from SLD facets.

SLD spectrum width is determined by optical gain spectrum width. When bulk heterostructures are used for SLD, SLD spectrum looks bell-like but is usually slightly asymmetric. Quantum-Well (QW) and Multiple QW (MQW) heterostructures allow to broaden SLD spectrum, but sometimes result in additional spectral distortions. Fig. 2 shows an example of SLD spectrum broadening by QW/MQW heterostructures at 820 nm: spectrum is broadened by two times from 20 nm in SLD-38 to 45-50 nm in SLD-37 (both products commercially available from Superlum). The use of MQW structures at 1500 nm band allows spectral broadening from 40 nm to more than 100 nm.

SLD coherence length is determined by FWHM of SLD spectrum, and may be expressed as :

$$L_c=k(\lambda^2/\Delta\lambda),$$

where λ is central wavelength, $\Delta\lambda$ is FWHM spectrum width, and k is coefficient which depends on spectrum form-factor (particularly, it is 0,32 for Lorentzian and 0,66 for Gaussian spectrum). It must be pointed out that coherence length is key SLD characteristic in a great number of low-coherence interferometry applications.

Parasitic Fabry-Perot modulation appears due to residual reflections from SLD crystal facets. In case of low residual spectral modulation depth, amplitude of residual Fabry-Perot modulation may be expressed as :

$$m = 2G(R_{out}R_{back})^{1/2} \text{ , (4)}$$

were R_{out} and R_{back} are residual reflections from the ends of active channel. When net gain reaches 30 dB gain (at 30 mW free space power), value of $R_{out}R_{back}$ must be as small as 10^{-10} to keep m at 2% peak-to-peak.

Finally, it is also necessary to count for so-called “secondary coherence effects”. Residual Fabry-Perot modulation results in parasitic subpeak in coherence function at the optical path difference at distance equal to $2n^*L_a$ were n^* is effective refractive index for optical mode and L_a is length of SLD. Intensity of such “secondary subpeak” is determined by spectral modulation depth; however, it may differ considerably (by the order of magnitude and even more) in SLDs with the same Fabry-Perot modulation index. The reason for this is that SLD parasitic spectral modulation is usually characterized around the top of spectrum where the modulation depth reaches its maximum value. Secondary subpeak intensity is determined by “integral” value of Fabry-Perot modulation across entire spectrum. If, to any reason, in one SLD residual spectral modulation of 1% is obtained only around the top of spectrum, but exists across entire spectrum in other, the second SLD will have much higher secondary coherence subpeak.

As an example of spectral and coherence properties of SLDs, Fig. 2 also represents spectrum and coherence function for SLD-381 diode with 22 nm spectrum FWHM and 1% residual Fabry-Perot modulation depth. Autocorrelation maximum is disturbed by some sidelobes due to asymmetric SLD spectrum.

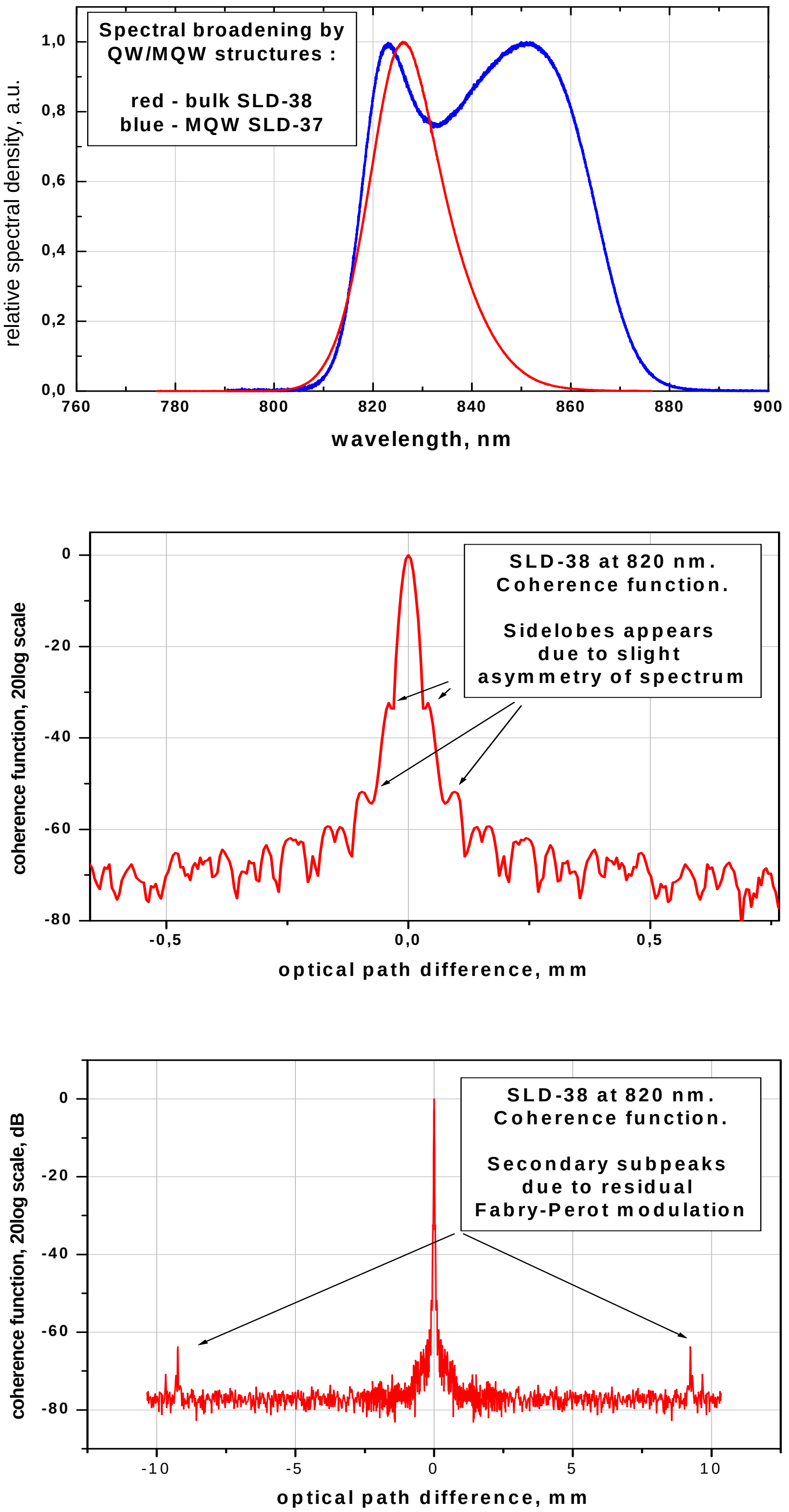


Fig. 2. Examples of SLD spectra and coherence functions

SLD and optical feedback

Extremely high optical gain in active region results in very high sensitivity of SLD to external optical feedback. In fact, any returned light will be amplified in SLD active region. Simple estimation shows that in case of 30 dB gain even 1% feedback will result in 10 times more photons on back SLD facet with respect to “feedback-free” operation. If gain is close to saturated value, this will result in decreased SLD output power. Fig. 3 shows calculated light-current characteristics of different SLD in case of different optical feedback. It is seen that even 1% of feedback deteriorates performance of high-power SLD very strongly : this may be the reason for fatal device failure due to Catastrophic Optical Damage of SLD facet (820 nm structures are known for relatively low COD; note for 10 mW singlemode fiber coupled SLD-381-HP module 1% optical reason back to SLD active region means just 4% backreflection from normal-cleaved fiber end). Re-distribution of driving current across the active region may degrade device lifetime, too.

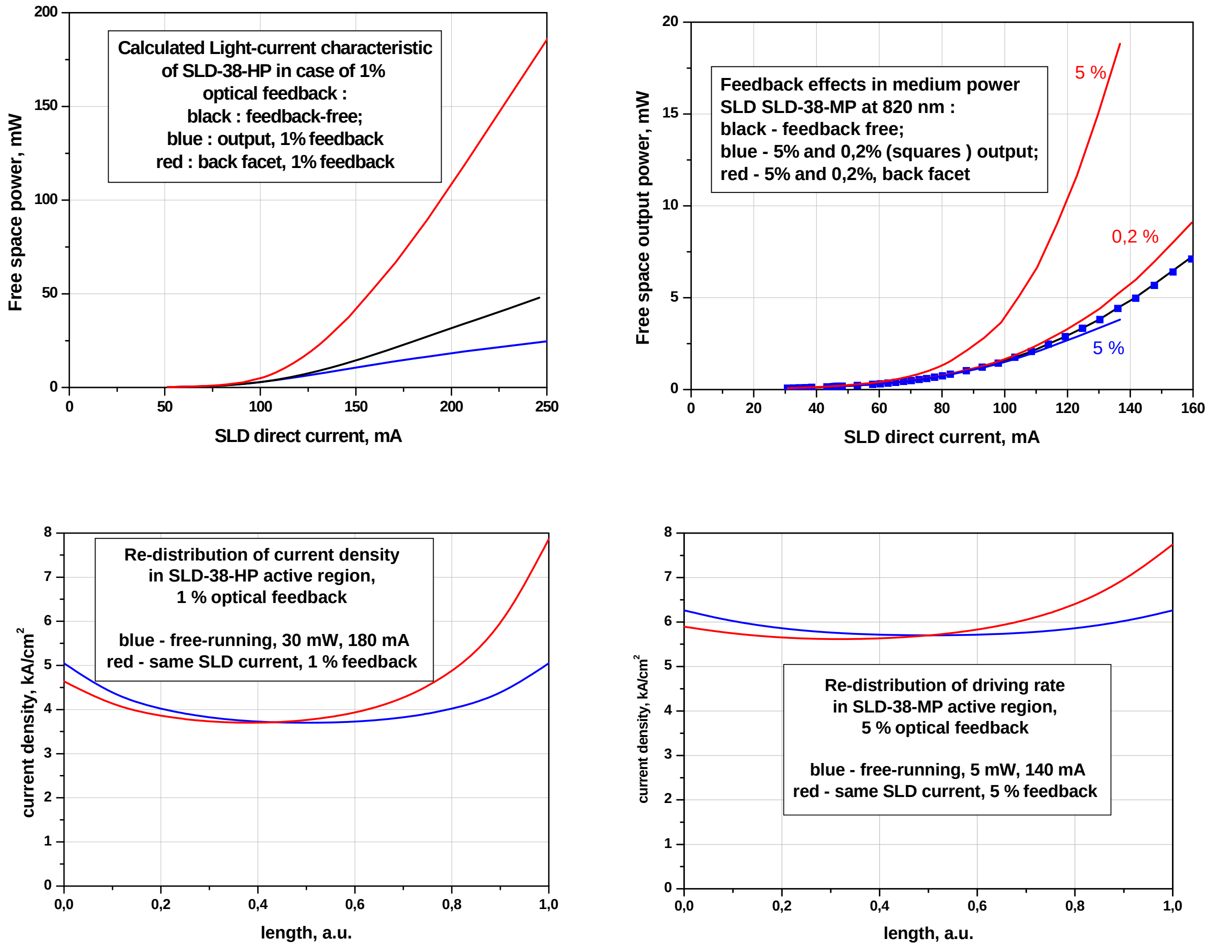
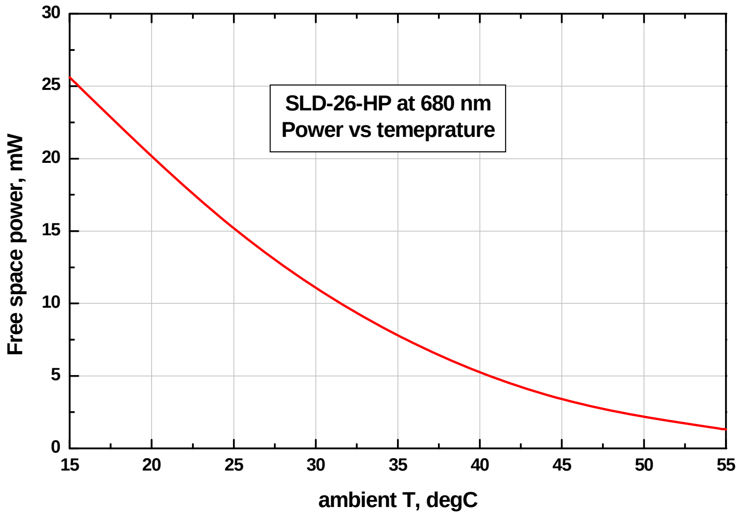


Fig. 3. Feedback effects in high-power and low-power SLDs.

Evidently, SLD sensitivity to feedback depends strongly on SLD gain. Fig. 3 also shows some feedback calculations for “medium-power” SLD-38-MP2 SLDs at 820 nm; 0,2% feedback corresponds to typical feedback coefficient in case of normal-cleaved singlemode fiber. In such SLD gain is less saturated, and the impact of feedback on output power is not so serious as in HP diodes. However, it may also affect stability and reliability of device.

Temperature performance of SLDs

Optical gain in semiconductors depends strongly on temperature. Due to this and due to exponential dependence of SLD power on gain, SLD power depends strongly on temperature, too. This problem is mostly serious at 680 nm band and at 1300 nm and 1550 nm bands, were optical gain dependence on temperature is really very strong. For example, power of 680 nm SLD degrades by 10 times when SLD temperature changes from +25 °C to +50 °C (see Fig.4). Due to high current density, increasing of SLD current cannot be used for compensation of power decreasing with temperature because this will reduce SLD lifetime significantly.



SLD central wavelength and spectrum width also change with ambient. This is hard to describe these changes shortly because they depend on driving mode (constant current or constant power), SLD structure (bulk or QW or MQW) and a number of other parameters. We would recommend contacting us for more details for each particular type of SLD.

SLD spatial characteristics

Most of SLDs emit at single transverse mode. However, as tilting of waveguide is one of mostly common approach to reduce reflections from output facets, SLD far field may be described as "crescent-like" laser diode far field. The example is shown on Fig. 5.

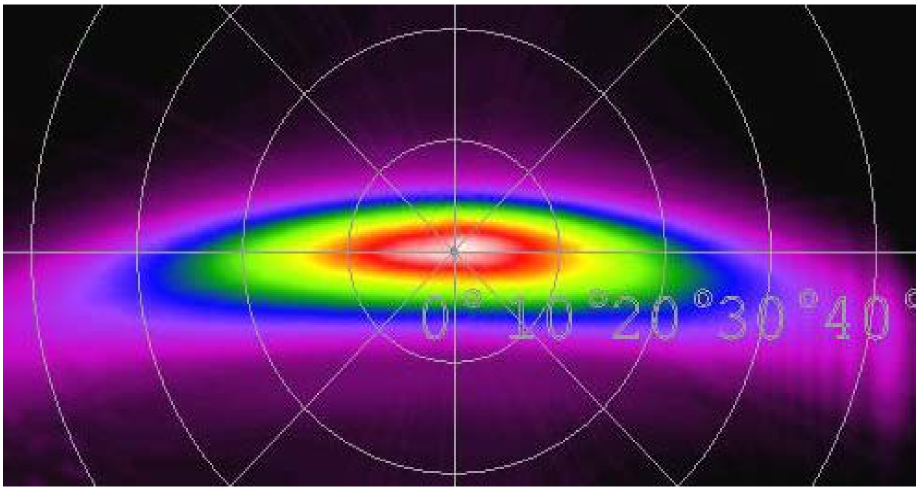


Fig. 5.

Single spatial mode emission allows high coupling efficiency to singlemode fiber: 20 – 40% coupling efficiency may be obtained by the use of spherical microlens on the fiber end, and it may be increased up to 60-70% by the use of cylindrical microlens.

SLD polarization

Polarization of SLD emitters depend strongly on their structure; there are some SLDs with TE/TM polarization ratio > 50:1, However, this is not the common rule, and there are SLDs which have it 3:1 ratio, or are depolarized (even when very powerful).

SLD noise

SLD noise spectrum is white (at least starting 100 kHz), with Relative Intensity Noise (RIN) value exceeding short noise ($2eI$, e - elementary charge, I - photocurrent) by about 30 dB for "mostly typical" SLD with output power 3 – 5 mW or high. RIN value does not depend on power strongly and ranges from -120 dB/Hz to -140 dB/Hz in different types of SLDs.

So-called 1/f-noise also exists in SLD. It usually dominates over white noise component starting 10 kHz or less; unfortunately there is not too much data about this phenomenon in SLDs.

SLD modulation

Usually, SLD are intended for use as CW light sources, and suppliers do not care too much about their modulation bandwidth. In practice, it should be possible to modulate directly any SLD emitter up to 100 MHz without considerable problems.

SLD reliability and lifetime. Driving of SLDs. Stability of SLD operation.

Lifetime of any light source is always determined by two key factors: natural lifetime and quality of its use.

The *"quality of use"* combines both workmanship on SLD and its driving. Being a kind of laser diodes, all SLD are to the same extent sensitive to electrostatic discharges, overheating, overdriving by spikes/surges, negative voltages, etc. One of mostly dangerous problem is the problem of "latent damages" which are hardly seen at first sight (performance parameters are practically unchanged after such damage), but which reduce lifetime to 1000 – 2000 h hours. At least the same safety measures must be obtained to drive SLD as that for laser diodes; the last are excellently described by ILX Lightwave, Inc., and all associated literature may be requested directly from ILX (www.ilxlightwave.com). However, we would like to point out two main distinctive features of SLD, which require even more careful use of these devices (with respect to laser diode):

- *Current "spike" damages SLD "much easier" than laser diode*. The reason for this is non-uniform distribution of driving current inside the active region of SLD. The higher is SLD current, the higher its fraction flows near crystal facet. Therefore, current spike will mainly flow through the areas nearby crystal facet, and this will additionally force probability of damage with respect to laser diodes. Latent damage nearby crystal facet, being the reason for extra reflection, may not effect SLD power considerably but may strongly increase SLD spectral ripple and makes device non-useable;

- *Minor optical feedback may easily result in fatal SLD damage*, especially if SLD is powerful. In laser diodes, parasitic feedback in range of 1% effects its performance but does not effect their lifetime (at least in most of cases).

In addition, some "second-order" effects shall be taken into account. Let us consider medium power 820 nm SLD running at 5% feedback. SLD output is not affected seriously; back-propagated power is below COD level. However, due to re-distribution of driving (see Fig. 3 above), effective driving density near back SLD facet is 20% higher with respect to feedback-free operation, and this may decrease SLD lifetime.

Natural lifetime is intrinsic property of SLD. It depends strongly on SLD material and design, as well as on SLD operation mode. Unfortunately, the matter of SLD lifetime is still investigated not well enough. One of the main reasons for this was a kind of common belief that, being a kind of laser diodes, SLD shall have the same lifetime as "the same" (i.e. single-transverse-mode, same-power-rated) LD. Neither statistics of failures, nor activation energies and other important parameters are studied well enough for SLD, at least accordingly to our analysis of available SLD literature.

However, "LD-like" approach is not correct because of at least two differences between SLD and LD:

- SLD are driven by considerably higher current; lifetime of laser diodes is known to be dependent on driving density, and in some structures (like AlGaAs for 780-850 nm wavelength) driving density is the key lifetime limiting factor;
- Non-uniform distribution of driving in SLD active region may speed-up degradation.

Accordingly with published data, SLD lifetime is 2 – 3 times less than lifetime of "similar" (in terms of output power laser diodes) : for example, 100 000 h Medium Time To Failure (MTTF) was obtained in medium-power SLDs at 820 nm with 3 – 5 mW free space output power, unless $\geq$200 000 h MTTF was expected from "similar" 820 nm laser diodes. In SLDs based on quaternary InGaAsP heterostructures (1300 – 1600 nm range), the impact of high driving current density on SLD lifetime reduction with respect to Laser Diodes shall be less. Currently, internal project is carried out at Superlum.

Short term stability of SLD operation is determined mainly by driving, including both quality of temperature stabilization and SLD driving current stabilization.