Study of the Mechanisms of Spectral Broadening in High Power Semiconductor Laser Arrays

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Abstract

High power semiconductor laser arrays have found increased applications in pumping of solid state laser systems for industrial, military and medical applications as well as direct material processing applications such as welding, cutting, and surface treatment. Semiconductor laser array products are required to have narrow spectral width for applications. Increasing the spectral accuracy by reducing the spectral width of the pump diode enables the laser system designer to improve the laser system compactness, efficiency, power, and beam quality while at the same time reducing thermal management cost in the system. Spectral width is one of the key specifications of laser array products and it is very important to improve the spectral performance to improve production yield, reduce cost and gain competitiveness. In this paper, we study the mechanisms of spectral broadening in high power semiconductor laser arrays.

Introduction

High power semiconductor lasers, including single emitters, arrays and stacks, have found increased applications in pumping of solid state laser systems for industrial, military and medical applications as well as direct material processing applications such as welding, cutting, and surface treatment [1-2]. With the power, efficiency, reliability, manufacturability, and cost of high power semiconductor laser technology continuing to improve, many new applications are being enabled. The three key performance measures of high power semiconductor lasers are power, efficiency, and reliability. However, for laser arrays, the spectral width is as important as the above three parameters as the spectral width of a laser array as a pumping source significantly affects compactness, efficiency, power, beam quality and thermal management of a laser system such as diode pumped solid state lasers and fiber lasers. All the pumping source energy out of the absorption bandwidth of the active laser media is wasted and becomes heat. A typical 808 nm high power semiconductor laser array (or more sometimes called laser bar) in a conduction cooled package has 19 to 49 individual emitters and the typical CW output power ranges from 30W to 100W. Figure 1 is an illustration of a high power semiconductor laser array. To achieve high efficiency and high CW power, Cu is commonly used as the heatsink (anode block) for laser arrays. To reduce the thermal stress applied on the laser array due to the mismatch of coefficient of thermal expansion (CTE) between the semiconductor laser and Cu anode, indium solder is commonly selected for die bonding. Most of the commercially available conduction cooled laser array/bar packages are in this format.

The spectral broadening of laser arrays is a result of non-uniform emitting wavelength from individual emitters. The broadened spectrum of a laser array/bar can have double or even multiple peaks; some may have shoulders or tails on either or both sides of the spectrum. The emitting wavelength from individual emitters is affected by wafer uniformity as well as packaging related thermal and thermal stress effects, with the latter being the major factor. The wavelength of an 808 nm laser shifts to the longer direction at a rate of ~0.27nm/°C. When the junction temperature of the emitters across the whole array is not uniform, the emitting wavelength varies. The CTE mismatch between the laser array and the mounting substrate material would cause thermal-stress in the package structure, which could be imposed on the laser array. Tensile or compressive stress in the epitaxial material of a laser affects the emitting wavelength with a coefficient on the order of ~$1*10^{-5}$ eV/bar (or ~0.005nm/bar), with tensile stress causing red-shift and compressive stress having blue-shift [3]. Non-uniform thermal stress experienced by the emitters across the width of the array would cause uneven wavelength and thus broad spectrum. In the paper, we study the mechanisms of different types of broadened spectral shapes of high power CW laser arrays/bars.

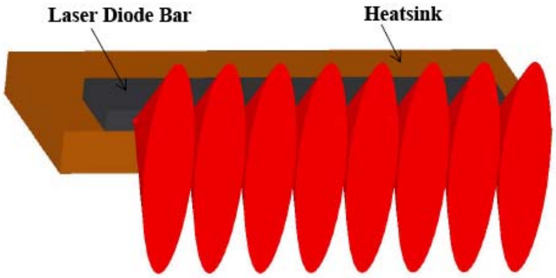


Figure 1. An illustration of a high power semiconductor laser array (laser bar).

Spectral Broadening

The spectral broadening of laser arrays is a result of non-uniform emitting wavelength from individual emitters. The emitting wavelength from individual emitters could be affected by wafer uniformity as well as packaging related thermal and thermal stress effects. However, as the individual emitters in a bar are close by and the material growth and wafer processing are pretty uniform, the wavelength variation among the individual emitters in a laser bar is generally small and is considered negligible compared to that caused by packaging related thermal and thermal stress effects. The parameters used to measure the spectral width are mainly full width half maximum (FWHM) and full width 90% energy (FW90%E) with FWHM being more commonly used. For most of the commercial products of 808nm laser bars, the specification of FWHM is commonly no greater than 3nm. Figure 2 shows a typical spectrum of a good laser diode array. The spectrum is in Gaussian shape. The broadened spectrum of a laser array/bar can have double or even multiple peaks; some may have shoulders or tails on either or both sides of the spectrum. Figure 3 shows some typical examples of broadened spectra of laser diode arrays. A broadened spectrum is generally no longer in Gaussian shape. Part of the energy out of the Gaussian distribution could not be absorbed by the active laser media and becomes heat, which negatively impacts the compactness, efficiency, power, and thermal management of a laser system. For a broadened spectrum, FWHM is no longer a good figure of merit to describe the spectral performance of a laser bar when there is a shoulder or tail below the half maximum value. Recently more and more companies begin to use FW90%E as a specification for spectral performance. The production yield loss due to wide spectrum (fails FWHM and/or FW90%E specification) could be significant. Furthermore, spectral broadening could be an indication of poor reliability of the laser array product depending the root cause of the spectral broadening. Therefore, it is very important to study the mechanisms of the spectral broadening and thus to improve the spectrum performance of the products to improve production yield, reduce cost and improve reliability. Conduction cooled 808nm CW laser array packages with different types of broadened spectral shapes are studied to identify the root causes of the corresponding broadened spectral shapes. The possible spectral broadening includes a shoulder, tail or secondary peak on the right side or left side or both sides the spectrum, or double or multiple peaks, which are showed in Figure 3 (a) to (d), respectively. The different broadened spectral shapes are related to the thermal or/and thermal-stress effects.

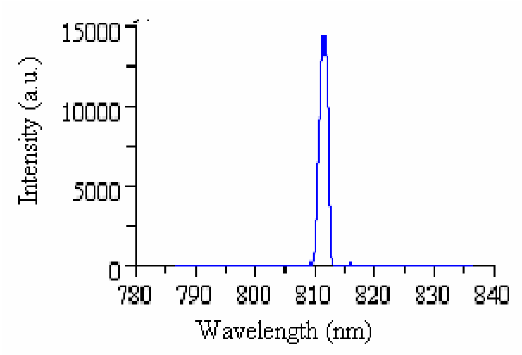
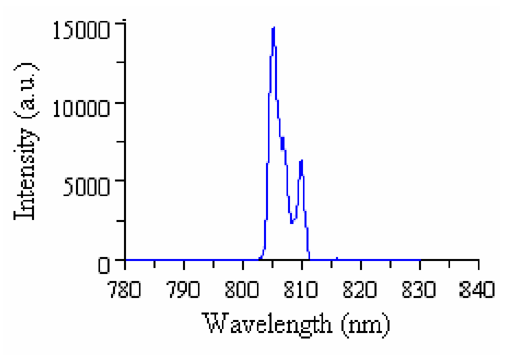
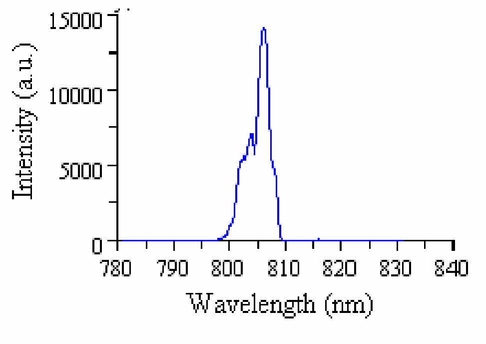


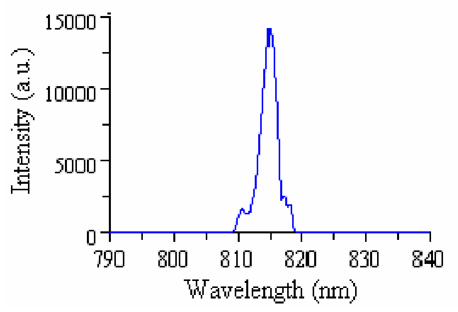
Figure 2. A typical spectrum of a good laser diode array.



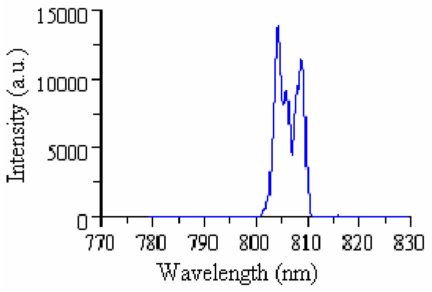
(a)



(b)



（c）



(d)

Figure 3. Typical examples of broadened spectra of laser diode arrays.

Experiments

Conduction cooled 808nm CW laser array samples with different spectral shapes shown in Figure 2 and Figure 3 were characterized using spatial spectral mapping, scanning acoustic microscopy and material analysis techniques to study the emitting wavelength of each emitter, wavelength distribution and package structure, especially die bonding. These samples are made of laser array bonded to Cu heatsink using indium solder. The indium solder thickness is between 4-6 μm.

Spatial spectral mapping of laser diode arrays can reflect the wavelength of each individual emitter in spatial dimension. Figure 4 shows the spatial spectral images of the laser array samples with different spectral shapes. The red dotted line is the main peak wavelength location in their respective spectrum shown in Figure 2 and Figure 3. Figure 4 (a) shows the spatial spectral image of the good laser diode array shown in Figure 2, which has a narrow and Gaussian shaped spectrum. As expected, the spatial spectral images of the emitters are pretty linear which indicates that the wavelength of the individual emitters in the laser array is pretty uniform. Figure 4 (b) to (e) shows the spatial spectral images of the laser array samples with broadened spectra shown in Figure 3 (a) to (d), respectively. We can see from Figure 4 (b) that the five emitters (the first right one is not clear due to measurement system) on the right side in the image have relatively longer wavelengths than majority of the emitters in the array. The light emission from these longer wavelength emitters forms a separate peak from that of the rest of the emitters corresponding to the secondary peak on the right side of the spectrum in Figure 3 (a). In the same manner, the light emission from the emitters at the center of the image in Figure 4 (c) creates the shoulder on the left side of the spectrum in Figure 3 (b). Similarly, from the images in Figure 4 (d) and (e), one can find out which emitters are responsible for the tails on both left and right sides of the spectrum and the double peaks shown in Figure 3 (c) and (d), respectively.

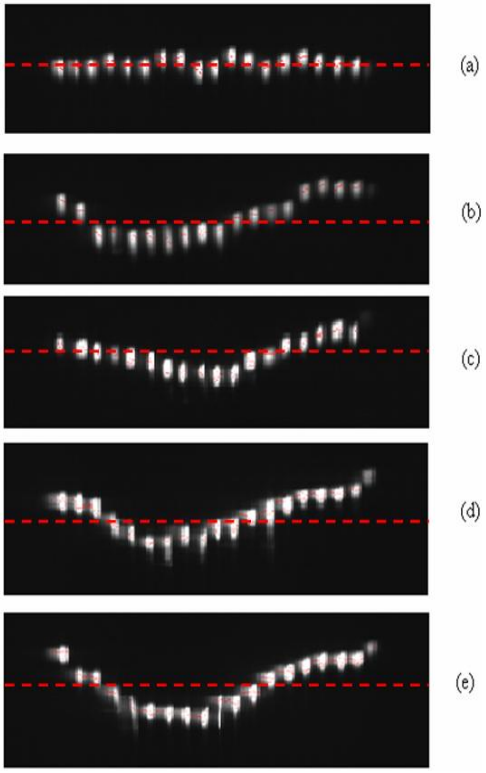


Figure 4. Spatial spectral mapping of the laser array samples with different spectral shapes; (a) good spectrum as shown in Figure 2; (b) spectrum having a secondary peak/shoulder on the right side as shown in Figure 3 (a); (c) spectrum having a secondary peak/shoulder on the left side as shown in Figure 3 (b); (d) spectrum having tails on both left and right sides as shown in Figure 3 (c); (e) spectrum having double peaks as shown in Figure 3 (d).

After completing electro-optical characterization including spectral measurement and spatial spectral mapping, scanning acoustic microscopy (SAM) was performed on these samples to investigate the laser array bonding solder interface. Figure 5 shows the SAM images of the laser array samples with different spectral shapes. The stripes in the SAM images are shadows of the emitters of the laser array. In SAM images, the light colored areas are shallow voids or of different acoustic impedance from the areas of dark color, and white colored areas are deep voids. We can see from Figure 5 (a) that the SAM image of the sample with narrow and Gaussian shaped spectrum shown in Figure 2 is pretty uniform across the laser array, which indicates there are no large solder voids and no significant acoustic impedance variation across the laser array. However, from Figure 5 (b), it can be seen that there are solder voids under the first five or six emitters on the right side of the laser array and the first two emitters on the left side. To verify the white colored regions have solder voids, the samples were cross-sectioned and examined using scanning electron microscope (SEM). Figure 6 is the SEM image of the cross-section of the solder interface under the second right emitter in Figure 5 (b), where the SAM image is the brightest which indicates large and deep solder voids. The color at the two ends of the SAM image in Figure 5 (c) is lighter than the central region. It indicates that the two ends either have shallow solder voids or different acoustic impedance from the central region. SEM results showed that the two ends do not have significant voids, but have thicker solder interface than the central region. Figure 7 (a) and (b) are typical SEM images of the cross-section of the solder interface under the emitters in the light colored and dark colored regions in Figure 5 (c). It can be seen that the solder interface in the light colored region has no significant voids and it is about 4-5 µm thick. There is a layer of pure indium

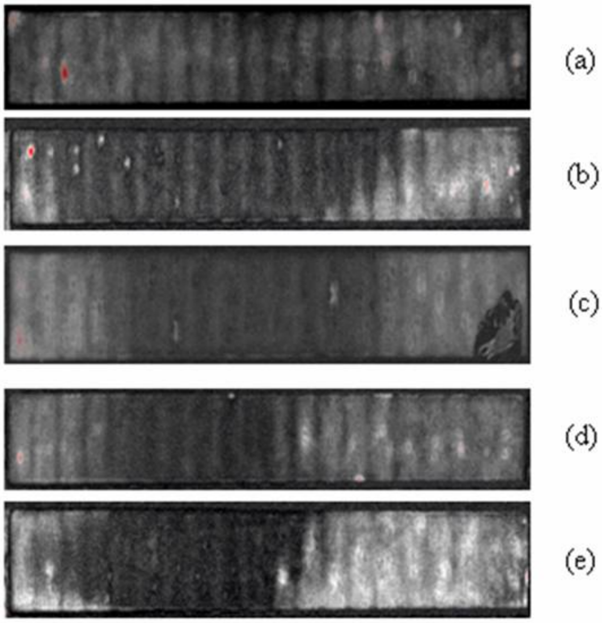


Figure 5. SAM images of the laser array samples with different spectral shapes; (a) good spectrum as shown in Figure 2; (b) spectrum having a secondary peak/shoulder on the right side as shown in Figure 3 (a); (c) spectrum having a secondary peak/shoulder on the left side as shown in Figure 3 (b); (d) spectrum having tails on both left and right sides as shown in Figure 3 (c); (e) spectrum having double peaks as shown in Figure 3 (d). Light colored areas are shallow voids or of different acoustic impedance from the areas of dark color, and white colored areas are deep voids.

in the interface although the indium solder forms intermetallics with the Cu heatsink which has Au finish and the metallization on the laser array on the lower and upper interfaces. The solder interface in the dark colored region has no voids either, but it is thinner (~2-2.5 µm thick) and there is no pure indium left in the solder interface. All the indium has been consumed to form intermetallics with the Cu heatsink and the metallization on the laser array. Figure 5 (d) is similar to Figure 5 (c). In addition, it has some while/bright spots in the light colored region. Figure 5 (e) is more similar to Figure 5 (b), but the white colored region is larger. SEM examination also confirmed that the solder layer under those emitters in the white colored region has voids.

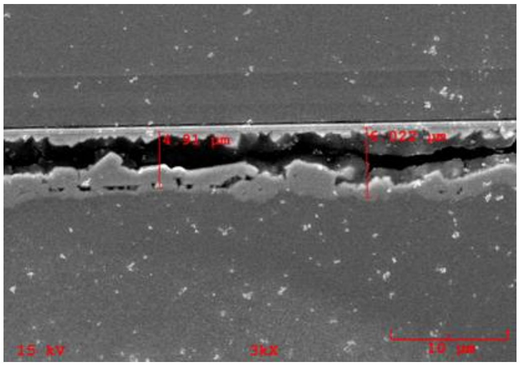
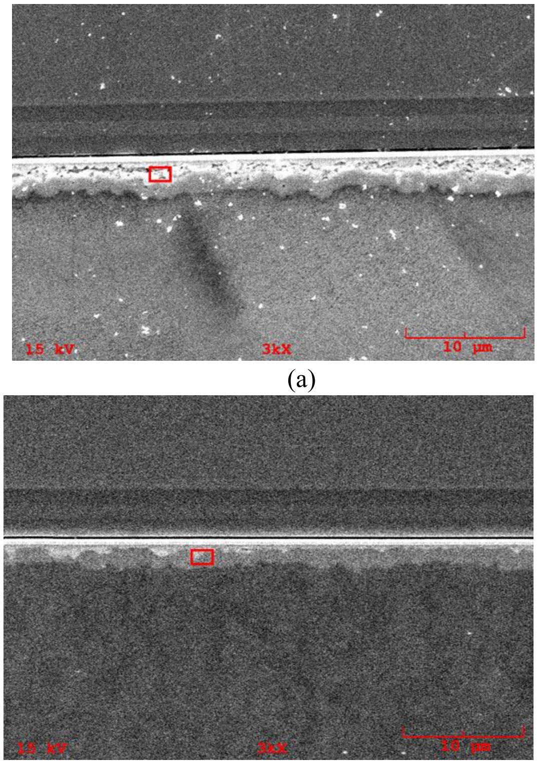


Figure 6. SEM image of the cross-section of the solder interface under the second right emitter in Figure 5 (b).



(a)

(b)

Figure 7. Typical SEM images of the cross-section of the solder interface under the emitters in the light colored and dark colored regions in Figure 5 (c); (a) corresponds to light colored region and (b) corresponds to dark colored region.

Discussion

The spatial spectral mapping results shown in Figure 4 identified which emitters in the laser array samples studied in this paper were responsible for the spectral broadening expressed in the secondary peaks, shoulders or tails shown in Figure 3. If there are significant numbers of emitters have longer or shorter wavelength than the original main wavelength (without additional thermal or thermal stress effect) of the laser array if the wavelength shift is far enough, there will appear a secondary peak in the spectrum or even double peaks. If only a small percentage of emitters have shifted wavelength from the original wavelength and the wavelength shift is not very large, there will have shoulder or tails in the spectrum. The spatial spectral images show that when there is a secondary peak, shoulder or tail on the right side (long wavelength side) of the spectrum, there are emitters that have shifted wavelength to the longer direction from the original main wavelength. When there is a secondary peak, shoulder or tail on the left side (short wavelength side) of the spectrum, there are emitters that have shifted wavelength to the shorter direction from the original main wavelength.

Scanning acoustic microscopy results revealed that there was no acoustic impedance variation at the bar attach solder interface across the laser array for the sample with good spectrum. For the spectral broadened samples, there are acoustic impedance variations in the solder interface among the emitters. SAM and SEM results showed that for the samples having a secondary peak/should/tail on the long wavelength side of the spectrum, there were voids in the solder interface. For the samples that having a secondary peak/should/tail on the short wavelength side of the spectrum, the acoustic impedance variations came from indium solder thickness variation. The solder interface was thicker at the two ends with a layer of pure indium. The solder became very thin at the central region and all the indium was consumed to form intermetallics which turned into a "hard" material.

Analyzing the spatial spectral mapping and SAM results obtained from the same samples, it is evident that the wavelengths of the emitters are very closely related to the solder interface. Figure 8 is the overlap of spatial spectral images with the SAM images obtained from the same samples. When the solder interface is uniform and free of large voids, the wavelength of the individual emitters are uniform and thus the laser array has narrow and Gaussian-shaped spectrum. From Figure 8 (b) and SEM results, we can see that the first five emitters on the right side of the array have large solder voids and correspondingly these five emitters (the first right one is not clear due to measurement system) have longer wavelength. The emitters to the left of these five emitters have less and less solder voids and the wavelength of these emitters gradually decreases. Similarly for the first left two emitters, there are some solder voids at these locations and the wavelength of them shifts to the longer direction. Same explanation can be applied to the sample in Figure 8 (e), only that the number of emitter having solder voids is greater than the sample in Figure 8 (b). As introduced previously, the wavelength of an 808 nm laser shifts to the longer direction at a rate of ~0.27nm/^{o}C. When the junction temperature of the emitters across the whole array is not uniform, the emitting wavelength varies. The junction temperature of the individual emitters is very sensitive to the solder voiding underneath the emitters as the lasers are epi-down bonded [4-5].

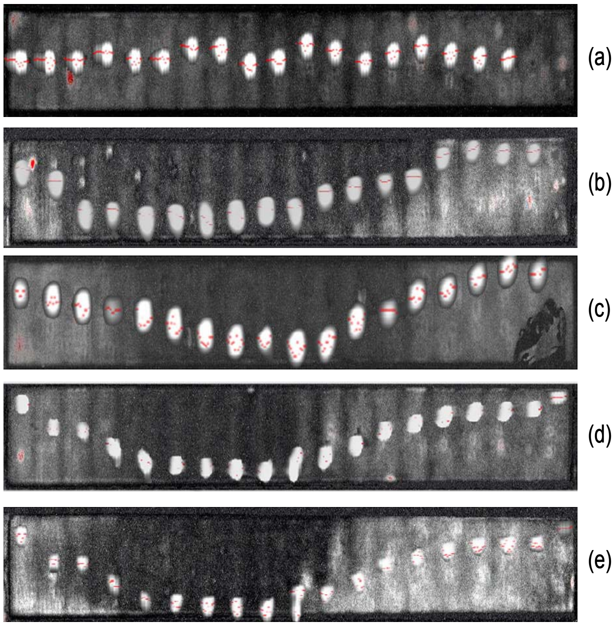
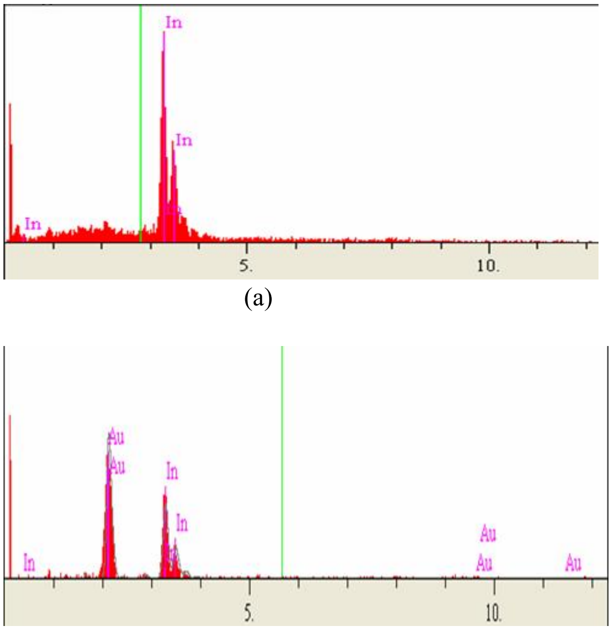


Figure 8. Overlap of spatial spectral images with the SAM images obtained from the same samples.



(a)

(b)

Figure 9. Energy dispersive X-ray (EDX) spectra of the materials at the location in the red box labeled in Figure 7 (a) and (b).

From Figure 8 (c), we can see that the emitters at the lighter colored region in the SAM image have longer wavelength than those at the dark region in the SAM image although SAM imaging and SEM results showed there were no significant solder voids in under the emitters at the lighter colored region. Therefore, the spectral broadening of this sample could not be explained by thermal effect. The fact that the spectral broadening occurred at the short wavelength direction and it is known that tensile or compressive stress in the epitaxial material of a laser affects the emitting wavelength with a coefficient on the order of ~$1*10^{-5}$ eV/bar (or ~0.005nm/bar), with tensile stress causing red-shift and compressive stress having blue-shift, the spectral broadening of this type can be attributed to thermal stress effect. Thermal stress is an inherent problem with the use of copper heatsink since copper has much larger coefficient of thermal expansion (CTE) than the laser array which is essentially made of GaAs material. With a CTE difference of ~$11\text{x}10^{-6}$ C^{-1} and a temperature difference of ~131 C between the indium solder freezing temperature, which is treated as stress free point, and room temperature, there is a ~14 μm of contraction difference between the Cu heatsnik and laser array along the length of the laser array for a standard 10 mm long laser array. This contraction difference causes compressive shear stress in indium solder layer. Soft indium solder can have plastic deformation and relax the thermal stress to a certain extent. By symmetry, the center of the laser array does not have shearing stress and the stress is more concentrated at the two ends of the array or somewhere between the center and the two edges when the stress near the edges of the array exceeds the yield strength of indium. Correspondingly, it is expected to see a minimum or no wavelength shift in the central region of the laser array and there may have some wavelength shift towards the shorter direction at the emitters at the two ends of the array or some emitters between the center and the two edges. However, the spatial spectral imaging result shown in Figure 4 (c) or Figure 8 (c) is not what is expected as described above. The above expectation is based on the assumption that there is a uniform layer of pure indium material at the solder interface. The SAM result shown in Figure 5 (c) and SEM results shown in Figure 7 revealed that the two ends have different acoustic impedance from the central region and the two ends have thicker solder interface than the central region. The central region no longer has pure indium left as all the indium was consumed during the soldering process to form intermetallics with the Cu heatsink which has Au finish and the metallization on the laser array while there remain a layer of pure indium although the indium solder forms intermetallics with the Cu heatsink and the metallization on the laser array on the lower and upper interfaces. Figure 9 (a) and (b) are the energy dispersive X-ray (EDX) spectra of the materials at the location in the red box labeled in Figure 7 (a) and (b), respectively. The EDX result confirmed that the porous layer in the solder interface under the emitters at the ends was pure indium material while the indium solder was completely consumed to during soldering process form AuIn intermetallics which become a hard material and can no longer relieve the thermal stress. The compressive thermal stress can be easily transferred to the laser array when there is no soft indium material left which leads to blue shift of wavelength at the central region. The intermetallics formation and indium consumption could be the same for the ends and the central region. However, the indium layer thickness at the two ends and central region may be different during the soldering process due to the laser array package design and/or soldering process. A good package design and/or optimized process can improve the spectral performance significantly [6]. The surface morphology measurement did show that the laser array was curved up after soldering which leads to thicker solder layer at two ends and thinner solder interface at the central region.

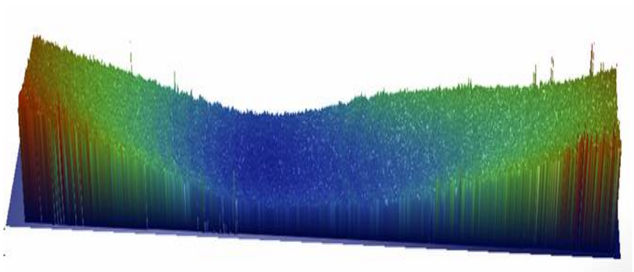


Figure 10. Top surface profile the sample shown in Figure 8 (c) which indicates the laser array is curved up.

Conclusions

Conduction cooled 808nm CW laser array packages with different types of broadened spectral shapes were characterized using spatial spectral mapping, scanning acoustic microscopy and material analysis techniques to study the emitting wavelength of each emitter, wavelength distribution and package structure, especially die bonding. It was concluded that while solder voiding causes local heating and therefore there could have a "shoulder" or "tail" on the right side of the spectrum, non-uniform thermal stress on the emitters could be the dominant factor in causing double or multiple peaks in spectrum. Intermetallic formation at some local die attach solder interface causes additional local compressive stress on some emitters, which lead to a "shoulder" or "tail" on the left side of the spectrum.

References

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