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Abstract. The distribution of light intensity of three light-curing units (LCUs) to cure the resin-based composite for dental fillings was analyzed, and a homogeneity index [flat-top factor (FTF)] was calculated. The index is based on the M^2 index, which is used for laser beams. An optical spectrum analyzer was used with an optical fiber to produce an x-y power profile of each LCU light guide. The FTF-calculated values were 0.51 for LCU1 and 0.55 for LCU2, which was the best FTF, although it still differed greatly from the perfect $FTF = 1$, and 0.27 for LCU3, which was the poorest value and even lower than the Gaussian $FTF = 0.5$. All LCUs presented notably heterogeneous light distribution, which can lead professionals and researchers to produce samples with irregular polymerization and poor mechanical properties. *© 2015 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JBO.20.5.055005]

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1 Introduction

The beam homogeneity of light-emitting diodes (LEDs) has always been of high concern because similar to lasers, the application field demands quality output. Example applications of LEDs include telecommunications, medical applications, industry use, illumination, CD players, and cell phones. A laser is usually selected when extreme monochromaticity and spatial brightness are required, whereas the LED output exhibits a wide-range spectrum, and filters must be used.[1] Furthermore, as noted by Schulze and Latimer,[2] the market still suffers from the lack of instrument consistency because LEDs are mass-produced and their spectrum and spatial distribution may vary from one supplier to another.

For both lasers and LEDs, the beam intensity distribution (or wavefront profile) is measured by scanning an aperture across the beam to acquire its power profile. This process can be performed by either taking a picture of the beam using a CCD camera and treating each pixel independently or scanning the beam in two dimensions with the tip of a 125/50 conventional optical fiber and measuring the power of each position on the other end of the fiber. The latter method was adopted in this paper.

After measuring the beam intensity distribution, the $1/e^2$ points are used to calculate the beam diameter, which is considered to have a pure Gaussian shape.[3] However, actual light beams contain other higher modes, so the $1/e^2$ technique does not properly specify the beam diameter. Therefore, a new parameter, which is called M^2, was created.[1] M^2 is the factor by which the diameter of the fundamental laser mode is multiplied to obtain the actual diameter of a beam, which consists of a mixture of several high-order models. The M^2 factor is also known as the beam quality, "times diffraction limit number" or the ratio of the beam divergence to that of the embedded Gaussian beam of a pure fundamental mode of the particular laser.[4] Thus, the M^2 factor is 1 for a pure Gaussian beam and increases when higher-order modes are added to the beam.

Pure Gaussian beams are perfect for many applications, such as open-space optics experiments. However, for industrial applications, laser beams with large M^2 values present larger focused spot sizes or smaller depth of field when they are tightly focused with large f-number optics. Therefore, higher M^2 beams are considered of lower beam quality.

In many industrial applications, there is a need to focus a laser beam to a well-defined size and shape while maintaining its intensity uniform, i.e., uniform irradiance over a defined section of the aperture. Particularly, the borders must have a notably precise boundary and sharp edges. This type of beam is called flat-top beam, where most of the power intensities inside the beam are identical. When the laser is used for cutting, a notably narrow transition region will create a clear border between the treated and untreated regions. Typical applications of flat-top beams include ablation, welding, cutting, hole drilling, scribing, laser displays, surgery, aesthetic treatment, and laser or LED resin curing.[5]

Although the M^2 factor is adequate for many industrial laser and LED applications, if one calculates the M^2 factor for a perfect flat-top beam, it will render $M^2 = \infty$ (Ref. 6) or notably large figures for the approximate flat-top beams, which are difficult to evaluate. Therefore, for the aforementioned

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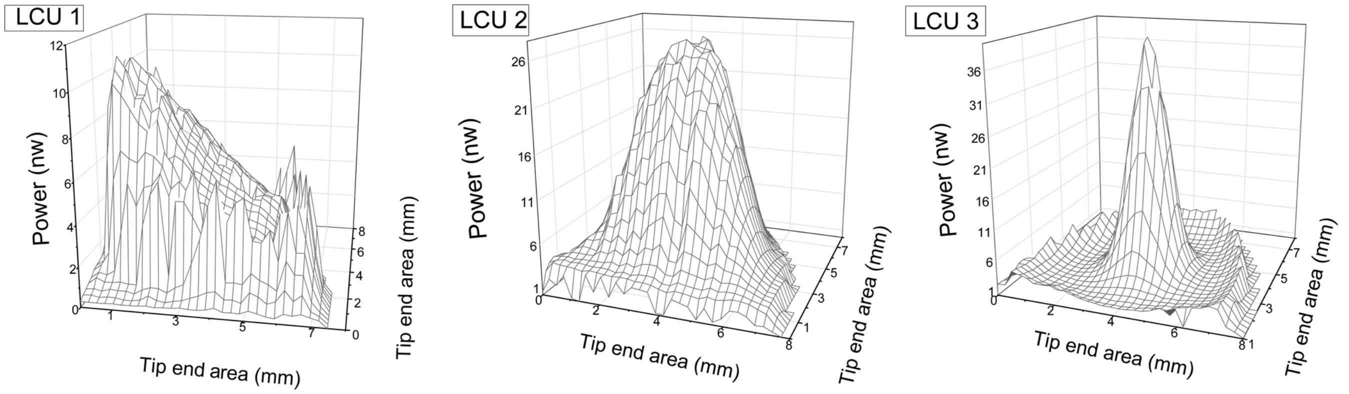

Fig. 1 Three-dimensional graphic of power distribution over the aperture of (a) LCU1, (b) LCU2, and (c) LCU3, measured by optical spectrum analyzer.

applications, the flat-top factor (FTF) is used. The FTF provides an intuitive idea of how homogeneous a beam is. A perfect square beam produces FTF = 1, whereas a perfect Gaussian beam yields FTF = 0.5. All real-world beams fall somewhere between 0.5 and 1. If some beams fall below 0.5, then the power distribution is notably poor, and extra care must be taken.

Light-curing polymer-based composites in odontology are particularly sensitive to the beam homogeneity because the material properties are determined by the degree of polymerization. Therefore, if the beam cannot reach the entire area to be polymerized with an identical intensity, several problems may arise, such as heterogeneous mechanical properties and internal stress. There are several studies in the literature that used the beam quality factor to evaluate the light curing unit (LCU) used in dentistry.[7,8] The authors reported severe light dispersion in some evaluated systems and concluded that this dispersion caused problems associated with the degree of conversion of the materials and consequently their mechanical properties.

In this study, the power light of three odontological LED–LCUs was measured by scanning the area of each tip end to analyze their power light homogeneity using the FTF and shape of their beam using three-dimensional (3-D) graphics.

2 Materials and Methods

Three LED curing unit systems (LCUs) that produce high-intensity light at 395 to 480 nm and can polymerize light-cured dental materials were analyzed in this work. The DB 686 (DabiAtlante) and Optilight Max (Gnatus) equipment use a rechargeable battery as an electrical source, and the Optilight LD MAX (Gnatus) is powered by an external power supply; these systems are referred to as LCU1, LCU2, and LCU3, respectively. All three LCUs have a light guide with an 8-mm-diameter tip end and one blue LED.

2.1 *Measurements*

The light power distribution at the tip end of each LCU was evaluated using an optical spectrum analyzer (OSA) (model AQ6373, Yokogawa, Japan). A conventional multimode optical fiber with 125 μm outer diameter and 50 μm core diameter was connected to the OSA input port. The other end of the fiber was fixed to an X-Y stage and placed near the tip end of the light guide, but there was no contact. Then, the system was manually moved in steps of 0.25 mm in both the x and y directions to scan the entire aperture of the LCU light guides. The LCU was turned on, and the peak of the light power was measured in nW and recorded for each X-Y position to create a bi-dimensional matrix with the measured values. From the measured power at each X-Y position, it was possible to construct a 3-D power distribution graph as shown in Figs. 1–3.

2.2 *Flat-Top Factor*

The FTF is a numerical measurement of quality for a beam profile. It is a normalized value that compares the beam profile against a perfect square beam profile. There are several procedures in the literature to calculate the FTF from the data obtained from X-Y beam scanning, such as in Ref. 9. Essentially, the following procedure should be performed: first, several levels of intensities from zero to the maximum measured intensity should be defined. To avoid redundancy, each level should be a few standard deviations apart from each other. Then, the histogram from the beam data, which are measured over the entire aperture image, should be calculated by counting the number of pixels with intensities inside each level defined. Then, the average intensity value is calculated as the ratio of the sum from all measurement values to the total number of pixels. The weighted histogram is obtained by multiplying each count value by the intensity value. Finally, the energy fraction curve is obtained by summing the weighted histogram from high to low intensities of each intensity level that was previously defined. The FTF is calculated by taking the ratio of the sum of all values in the weighted histogram or the area under the curve.

This procedure can be easily programmed in Microsoft Excel® software.

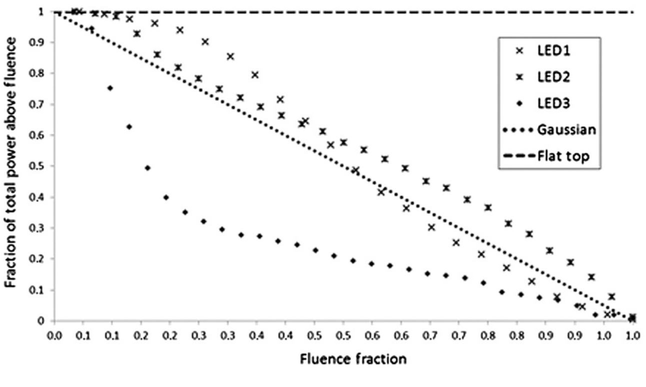

Fig. 2 Power fraction of the three light curing units (LCUs). Dotted line represents a pure Gaussian distribution, whereas dashed line represents a perfect flat-top distribution.

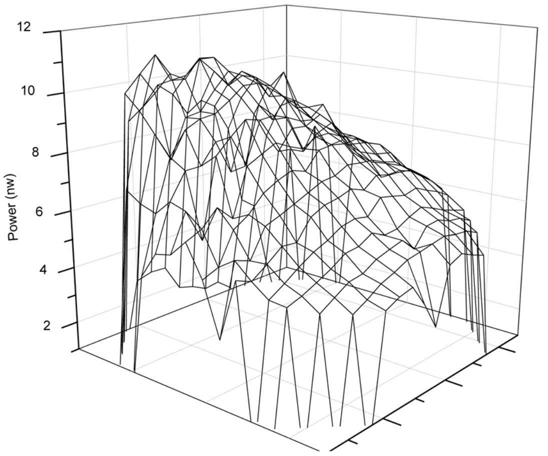

Fig. 3 Distribution power of the flattened LCU1, presenting sharper edges as compared with the graphs in Fig. 1.

3 Results and Discussion

Figures 1(a)–1(c) show the 3-D power profile of each LCU.

Even without evaluating the beam quality of the three LCUs, it is possible to conclude based on the graphs in Fig. 1 that LCU1 shows a nonuniform profile and that LCU2 and LCU3 show more Gaussian-like profiles. Furthermore, LCU2, which has a wider beam than LCU3, can lead to a more regular polymerization of the resin-based composite for dental fillings and consequently better mechanical properties. However, for the three cases, light distribution is far from the ideal flat-top profile.

From the obtained data for the light power measurements of each LCU, the FTF of each LCU was calculated using the described procedure in the previous section. Table 1 summarizes the results.

As expected, LCU2 showed the best FTF of 0.55, although it is far from FTF = 1, which is the perfect flat-top case. LCU3 had the poorest result, which is even less than the Gaussian FTF = 0.5. Figure 2 shows the fraction of total power above the fluence of the three LCUs. The lines that correspond to the Gaussian and flat-top behaviors are also shown in the figure for reference.

It is easily noticed that LCU3, which exhibited the poorest power distribution, ran well below the Gaussian distribution (dotted line) with FTF = 0.27. Although LCU1 started notably near the flat-top behavior, it constantly decreased and crossed the Gaussian line by half power, which resulted in FTF = 0.51. The best result was obtained by LCU2, which exhibited a fraction of total power above fluence that was always above the Gaussian line with FTF = 0.55.

Table 1 Results obtained from each light-curing unit (LCU).

Parameter/LCU	LCU1	LCU2	LCU3
Total power density[a]	420 mW/cm^2	680 mW/cm^2	780 mW/cm^2
Peak power[b]	10.21 nW	27.14 nW	39.82 nW
Total area	0.5 cm^2	0.5 cm^2	0.5 cm^2
Total power output	210 mW	340 mW	390 mW
FTF	0.51	0.55	0.27

[a] Over the whole aperture.
[b] Over 50-μm diameter aperture.

Because the average mezzo-distal width in posterior dental fillings is 5 mm,[10] a light guide with an FTF closest to 1 is the ideal choice to obtain the most homogenous light distribution and consequently homogeneous polymerization. All three analyzed LCUs are far from the ideal situation, and they act more quickly and efficiently in the center of the exposed area than at the borders. This result can lead to heterogeneous curing, underpolymerized regions, which are mainly near the borders, and different mechanical properties of the cured material. Furthermore, several problems can be associated with this lack of physical and mechanical properties of composite resin-based dental filling,[11] such as premature failure, color changing,[12] and allergic reactions.[13]

Because irregular polymerization can produce a sample with different micro- and macro-structures and the failure can be related to the material, studies should pay special attention to the light power distribution to prevent misidentification of the actual failure source.

3.1 *Flattening LED Beams*

There are optical techniques to convert Gaussian beams to flat-top beams, such as using a deformable mirror[14] or a focusing lens with a diffractive pattern.[5] However, these solutions are complex open optics techniques and differ greatly from the scope of LCUs that are applied to odontology, which must be simultaneously light, cheap, easy to use, and reliable.

For the present application, a viable method of flattening the beam is shading the low-power areas at the edge of the beam waist using an iris or a fixed aperture. The light that is allowed to cross the aperture will have sharper edges but lower power. However, the low power can be circumvented by increasing the curing time.

To test this hypothesis, one can simulate an aperture that is 50% smaller than the original over the x-y power distribution of an LCU and recalculate the FTF of the resulting power distribution. This procedure could not be performed for LCU3 because it only has high power at the center of the aperture. For LCU1 and LCU2, the simulation was performed using a 4-mm-diameter aperture.

Because LCU1 has a decentered peak power, the aperture was centered at the peak (not at the geometrical center). Then, the light that passed through this aperture was analyzed to produce the power distribution in Fig. 3. The identical procedure was performed for LCU2, which was centered at its peak power, to produce the power distribution in Fig. 4. Both cases exhibited sharper edges than the graphs in Figs. 1(a) and 1(b).

The performed FTF analysis for the data of the flattened LCUs exhibited a better flat-top performance, where FTF = 0.68 for the flattened LCU1 and FTF = 0.65 for the flattened LCU2.

Figure 5 shows the power fraction of the two flattened LCUs. The fraction for both LCUs is always above the Gaussian. Despite the improved FTF, the two LCUs showed a total power reduction because the aperture area is 50% smaller than that of the original light guide output area. The new output power can be evaluated as follows.

The total power of LCU1 (Table 1) is 210 mW, and the total analyzed power using the optical fiber tip as a probe is 3478 nW, as calculated from the histogram over the entire set of measurements. Now, if one takes the same result from the histogram

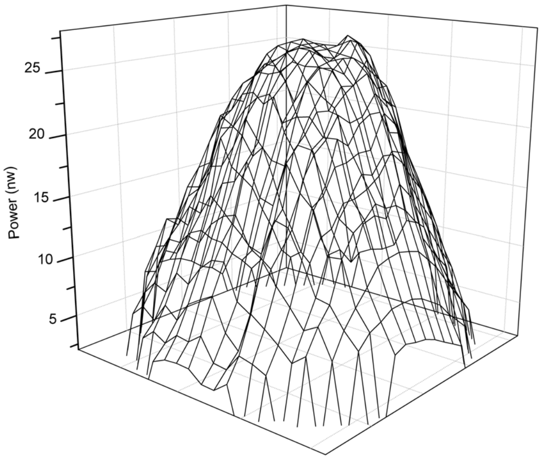

Fig. 4 Distribution power of the flattened LCU2, presenting sharper edges as compared with the graphs in Fig. 2.

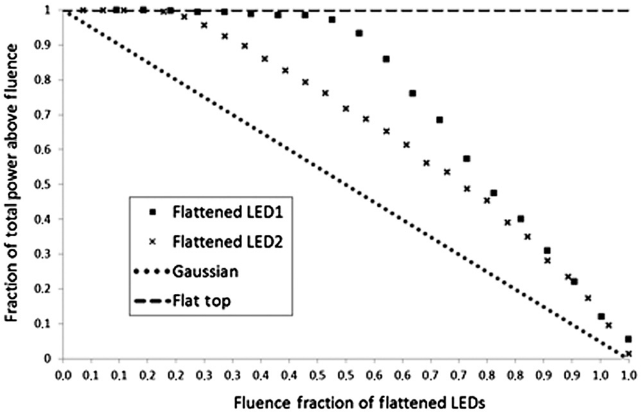

Fig. 5 Power fraction of two flattened LCUs. Dotted line represents a pure Gaussian distribution, whereas dashed line represents a perfect flat-top distribution.

over the flattened power distribution, a value of 1702.5 nW is obtained. One can apply this reduction on the total power, which yields a new total power of ∼103 mW, which is a reduction of ∼51%. Applying the identical calculation for LCU2 (340 mW) (6632 nW analyzed and 5323 nW when flattened), a total output power of 272 mW is obtained, i.e., a reduction of only ∼20%. The total power of each LCU was evaluated using a calibrated sensor (Absolute Spectral Response, Standard Solar Cell Ser. No. 00086; Centralab Semiconductor). However, if the power density of each LCU was recalculated according to the area of the flattened LED beams (4 mm diameter), LCU1 and LCU2 would have a significant increase in irradiance. LCU1 would have an approximate gain of 100%, and LCU2 would have an approximate gain of 200% compared to the total power density. This gain in irradiance certainly ensures more efficiency in the polymerization process. These results are summarized in Table 2.

Table 2 Results obtained from the flattened LCUs.

Parameter/ LCU	LCU1	Flattened LCU1	LCU2	Flattened LCU2
Total power output	210 mW	103 mW	340 mW	272 mW
FTF	0.51	0.68	0.55	0.65
Power density	420 mW/cm^2	820 mW/cm^2	680 mW/cm^2	2165 mW/cm^2

4 Conclusion

All three tested LCUs showed power distributions that were far from the ideal FTF = 1. This situation can lead dentists or researchers to produce weak dental fillings or samples with irregular polymerization and result in misidentification of the actual failure causes for the final polymerized material.

The aperture technique to flatten the LCU beams can be applied to some LCUs with an increase in the flat-top performance and relatively low power losses, but the power density will drastically improve.

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