Pump combiner loss as a function of input numerical aperture power distribution

Benoit Sévigny, Pierre Poirier and Mathieu Faucher

ITF Laboratories, 400 Montpellier Blvd., Montréal, Québec, H4N 2G7 Canada

ABSTRACT

High-power combiner designs (such as kilowatt-class combiners and beyond) are increasingly aggressive on brightness conservation in order to reduce the brightness loss of the pumps as much as possible in both direct diode combining and pump and signal coupling, especially with the advent of next-generation high-power pumps. Since most of the pump loss is due to brightness loss across the combiner, tighter designs (close to the brightness limit) are considerably more sensitive to variations in the input power distribution as a function of numerical aperture ; for instance, next-generation, high-power multi-emitter pumps are likely to have larger numerical apertures than conventional single-emitter diodes. As a consequence, pump insertion loss for a given combiner design sitting close to the brightness limit should be dependant on the input power distribution. Aside from presenting a manufacturing challenge, high brightness combiners also imply more sophisticated testing to allow a deeper understanding of the loss with respect to the far-field distribution of the pump inputs and thus enable the extrapolation of loss for an arbitrary, cylindrically symmetric radiant intensity distribution. In this paper, we present a novel test method to measure loss as a function of numerical aperture (NA) fill factor using a variable NA source with square-shaped far field distributions. Results are presented for a range of combiners, such as 7x1 and 19x1 pump combiners, with different brightness ratio and fiber inputs. Combiners violating the brightness conservation equation are also characterized in order to estimate the loss as a function of input power vs. NA distribution and fill factor.

Keywords: Brightness conservation, high brightness combiners, pump and signal combiners, pump combiners, fiber lasers and amplifiers, direct diode applications, kilowatt-class combiners.

1. INTRODUCTION

High-power pump combiner designs as well as pump and signal combiner designs[1–4] become more and more demanding in terms of brightness conservation, whether they are to be used in direct diode applications or in all-fiber lasers[5] or fiber amplifier systems. In particular, high-power next-generation pumps using multiple single-emitters are likely to have wider radiant intensity than current single-emitter diodes. Thus, in order to characterize the "safe range of operation" for a given low brightness ratio combiner design, pump insertion loss must be measured as a function of the far field power distribution of the pump inputs. In this paper, we present a method to perform such measurements and explain how the results can be used to estimate the loss with respect to known, arbitrary input pump NA power distribution. Such a test procedure is of great interest for high-power, kilowatt-class combiners using high-power, nearly fully filled pump inputs.

2. BRIGHTNESS RATIO AND COMBINER LOSS

Brightness conservation is a concept of utmost importance when designing a pump combiner. In general, total integrated brightness is considered for combiner designs since it reflects the worst case scenario for which all inputs are fully filled. "Fully filled" means that each point of the fiber core surface for a multimode fiber is emitting with a uniform radiant intensity per unit area distribution or "cone" up to the acceptance angle of the fiber (referred to as ϕ, see Figure 1). Thus, the *integrated brightness* (IB) of a fiber can be calculated simply by direct integration :

$$\mathrm{IB} = AR\int_0^{\Omega_\phi} \mathrm{d}\Omega \propto A\int_0^{\phi} \sin(\varphi)\mathrm{d}\varphi = A[1-\cos(\phi)]. \tag{1}$$

Further author information: (Send correspondence to Benoit Sévigny)
E-mail: bsevigny@itflabs.com, Telephone: (514) 748-4848 ext. 6474

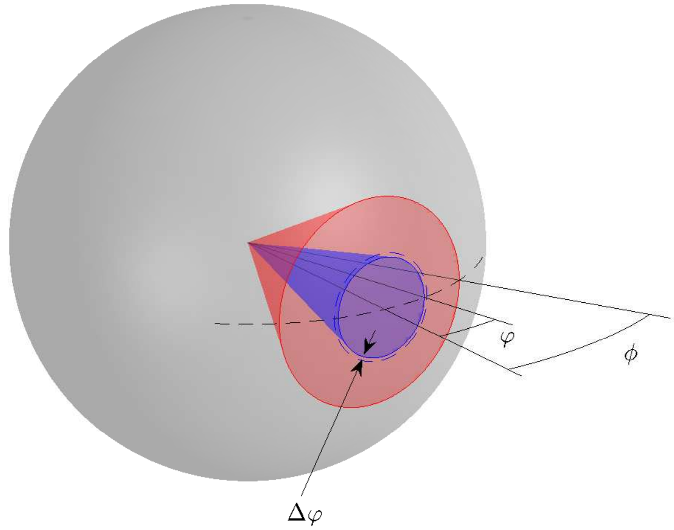


FIG. 1. Illustration of the uniform radiant intenstity distribution considered for the input fibers of a pump combiner. ϕ is the acceptance angle of the fiber and φ represents the integration parameter. The solid angle increment is thus given by $\Delta\Omega = 2\pi\sin(\varphi)\Delta\varphi$.

where A is the fiber area and R is the radian intensity profile. For small values of ϕ, and considering the fact that the numerical aperture (NA) of the fiber is proportional to $\sin(\phi) \approx \phi$, we can also express the integrated brightness as :

$$\mathrm{IB} \propto A[1-\cos(\phi)] \approx \frac{A}{2}\mathrm{NA}^2. \tag{2}$$

Integrated brightness is proportional to the total power in the fiber. By comparing the integrated brightness of the total input of a pump combiner to the integrated brightness of the output fiber, a loss figure can readily be estimated through the *brightness ratio* (BR). The brightness ratio is defined as[6,7] :

$$\mathrm{BR} = \frac{D_{out}^2\,[1-\cos(\phi_{out})]}{nD_{in}^2\,[1-\cos(\phi_{in})]} \approx \frac{D_{out}^2\mathrm{NA}_{out}^2}{nD_{in}^2\mathrm{NA}_{in}^2} \tag{3}$$

where D_{out} and D_{in} are the diameters of the output and input fibers respectively, ϕ_{out} and ϕ_{in} are respectively the acceptance angle of the output and input fibers (in air), NA_{out} and NA_{in} represent the NA of the output and input fibers respectively and n is the number of inputs. In order to take into account the worst case scenario, the number of ports n should be equal to the total number of input ports. For example, an $(N+1)\times 1$ pump and signal combiner should have a value $n = N+1$ to take into account, for instance, leakage of the pump light in the input signal fiber. The "leakage" process or any other NA increase or area increase process will be referred to as *brightness loss*. Figure 2 shows the theoretical pump combiner transmission for different values of the brightness ratio. This result suggests that combiners should be designed to have a value $\mathrm{BR} \geq 1$.

3. PROPOSED MEASUREMENT METHOD

The measurement method proposed requires the use of a variable NA source. The NA distribution of the source has constant radiant intensity R, is angularly symmetric (analogous to the cone shown on figure 1) and has adjustable width, allowing us to measure the transmission as a function of the width of the NA distribution. The total input power is given by :

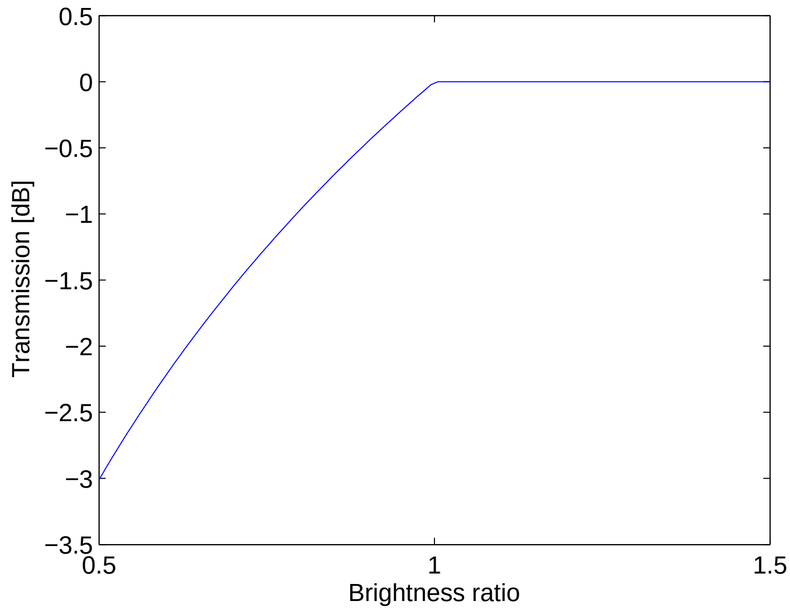


FIG. 2. Theoretical loss as a function of brightness ratio. In theory, if no brightness loss occurs in a combiner, values of BR larger than one should yield combiners with no loss. In reality, there is always some amount of brightness loss occuring in combiners through various processes, which makes this theoretical value a limit that cannot be exceeded.

$$P_{in} = R \int_0^{\Omega_{\mathrm{NA}}} \mathrm{d}\Omega = 2\pi R \int_0^{\phi_{\mathrm{NA}}} \sin(\varphi)\mathrm{d}\varphi = 2\pi R[1 - \cos(\phi_{\mathrm{NA}})] \approx \pi R \mathrm{NA}^2, \tag{4}$$

and the output power can be expressed as :

$$P_{out} = R \int_0^{\Omega_{\mathrm{NA}}} T(\Omega)\mathrm{d}\Omega = 2\pi R \int_0^{\phi_{\mathrm{NA}}} T(\varphi)\sin(\varphi)\mathrm{d}\varphi \approx 2\pi R \int_0^{\mathrm{NA}} T(\mathrm{NA}')\mathrm{NA}'\mathrm{dNA}' \tag{5}$$

where $T(\mathrm{NA})$ is the differential transmission as a function of NA. This measurement technique is of utmost interest for designs which have a value $\mathrm{BR} \leq 1$ (when considering the filled NA of the fibers) that could work for inputs with smaller NA distributions.

3.1 First measurement method : direct loss for uniform radiant intensity or "filled" input

In the case where the input of a combiner is known to be a uniform radiant intensity distribution and the transmitted power of the input "launch" fiber as well as the transmission of the device for an input distribution of given NA width are known, the loss as a function of source NA can be directly evaluated through the following formula :

$$\mathrm{T} = P_{out} - P_{in} \quad [\mathrm{dB}]. \tag{6}$$

This type of input is referred to as a *filled* input since the radiant intensity is constant and maximum all the way to the width of the distribution. The case where the NA (or NA width) of the distribution is equal to the maximum value of the input fiber is referred to as "fully-filled". Combiners manufactured at ITF Labs' facilities are typically tested under this condition. When the input of the device is a commercially available pump, the input radiant intensity distribution tends to be *underfilled*, meaning that the radiant intensity profile is not uniform and decreases slowly towards the specified NA, often specified at $1/e^2$ of the maximum value of R. This is especially true for single-emitter pumps. In this case, the measurement method described in this section tends to yield higher loss than what is typically observed when the device is operated within a real system. This is mainly due to the fact that high-NA light has a more important contribution to the loss, as shown in equation 5. An additional flaw inherent to this measurement method is that it includes the coupling loss at the input of the device (such as splice loss and so on). This value, if known, could be subtracted from the transmission value, although it could be NA dependent, in which case a cut-back measurement as a function of input NA is necessary to estimate the coupling loss adequately.

3.2 Second measurement method : derivation of $T(\mathrm{NA})$ and extrapolation for underfilled inputs

The transmission function $T(\mathrm{NA})$ can be retrieved through the measurements of P_{out} and P_{in}. Indeed, knowing the input and output powers while assuming R to be constant and angularly symmetric (i.e, not elliptical), one can derive the value of $T(\mathrm{NA})$ by differentiation :

$$T(\mathrm{NA}) = \frac{\partial P_{out}}{\partial P_{in}} \approx \frac{\Delta P_{out}}{\Delta P_{in}}. \tag{7}$$

Thus, with this information, it is possible to estimate the transmission T of the device for a source with arbitrary power distribution as a function of NA, $R(\mathrm{NA})$:

$$\mathrm{T} = 10\log_{10}\left[\frac{2\pi}{P_0}\int_0^{\mathrm{NA_{max}}} R(\mathrm{NA}')T(\mathrm{NA}')\mathrm{NA}'\mathrm{dNA}'\right] \quad [\mathrm{dB}], \tag{8}$$

with

$$P_0 = 2\pi\int_0^{\mathrm{NA_{max}}} R(\mathrm{NA}')\mathrm{NA}'\mathrm{dNA}'. \tag{9}$$

This algorithm represents a simple way to estimate the loss of a combiner for an input with arbitrary angularly symmetric radiant intensity profile $R(\mathrm{NA})$. Thus, from the transmission data as a function of filled NA, one can extrapolate what the loss of an arbitrary pump input would be for the same device. This powerful method could be applied to multiple inputs for a single device (see, for example, figures 5 and 6). However, the biggest flaw of this method resides in the numerical differentiation required to retrieve $T(\mathrm{NA})$, which makes the final result very sensitive to power or NA fluctuations and so on, in the filled source used for the measurement. Such fluctuations can be reduced, for example, by using a source with very stable power output or by fitting the expirimental $T(\mathrm{NA})$ function with an adequate function type to minimize the impact of irregularities when integrating the total transmission T.

4. EXPERIMENTAL SETUP

The experimental setup is illustrated on figure 3. A strongly multimode, pigtailed source is collimated to obtain a parallel beam with uniform intensity distribution. An adjustable iris samples the collimated beam and the collimated part is then coupled into the launch fiber by the focusing lens. Diffraction by the iris puts a lower limit on available excitation NA values. A goniometer is used to measure the radiant intensity distributions and power measurements are performed with an integrating sphere coupled to a detector.

5. EXPERIMENTAL RESULTS

In this section, numerous results will be presented for two different $N \times 1$ combiners, one of them with a value of $\mathrm{BR} < 1$. Examples will be given for various case scenarios covering both calculation methods presented in section 3.

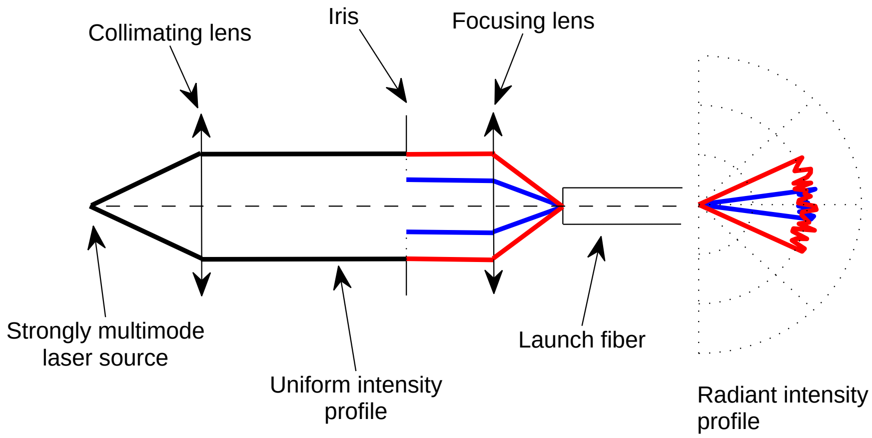
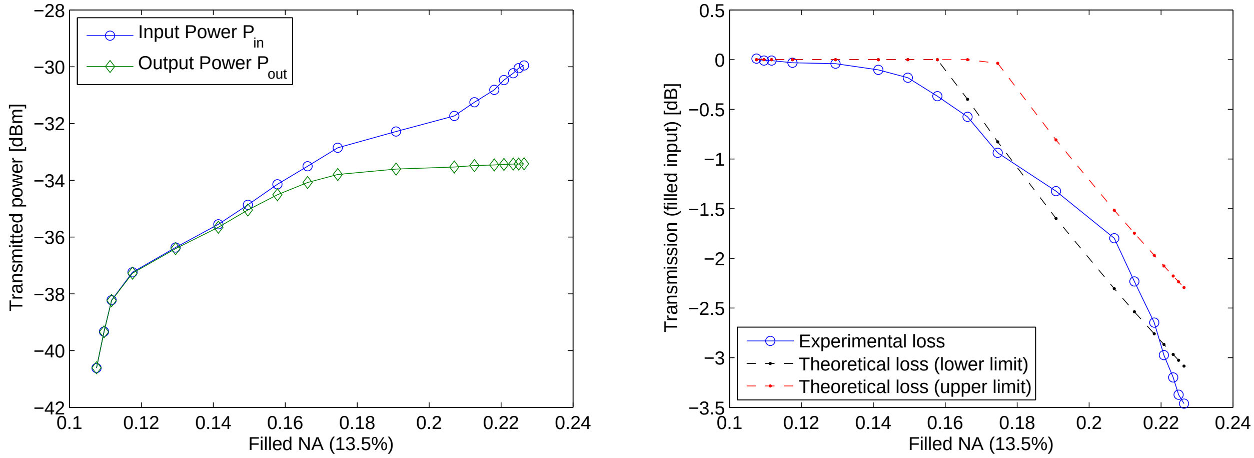


FIG. 3. Setup used to inject light in the combiner. A strongly multimode laser is collimated and then sampled through an adjustable iris. The output is then refocused and coupled into a launch multimode fiber which will be spliced to the combiner inputs. The calibration measurements, both in power and NA, are performed at the output of the launch fiber.

5.1 7×1 design with BR>1

The first design to be studied is a 7×1 combiner with 200 μm core, NA=0.15 inputs and a 400 μm core, NA=0.22 output. This design has a value of $\mathrm{BR} \approx 1.2$. Thus, in this case, loss should be farily low, even to the fully-filled input NA of 0.15. Figure 4 (a) shows the power vs. NA curves for the input (reference) fiber as well as the averaged output power for all ports. Figure 4 (b) shows the computed loss as a function of measured NA for this combiner calculated from Eq. (6) as well as both theoretical limits (given by the brightness ratio) for the lower and upper limits of the output fiber NA. As we can see, the breakoff NA value of the theoretical curves lies a bit above NA=0.15, which should be the case since this combiner has $BR \geq 1$. Loss values above the breakoff NA values are expected to fall rapidly and take into account both the filtering of the input fiber (which has an NA of 0.15 within tolerances of 0.01) as well as the loss of the combiner itself, accounting for brightness loss across the combiner. All those results were obtained using a filled input radiant intensity distribution with the corresponding NA measured at 13.5% of the maximum value. As we can see from figure 4 (b), this combiner should behave fairly well (with low loss of about -0.3dB) at the normal operating NA of 0.15 (filled). It is also to be noted that splice-related loss at very low NA is negligible, as shown in the plot of figure 4 (b), since the calculated loss is marginal at low NA values. This, however, is not necessarily applicable for higher NA values due to the splice between dissimilar fibers (the launch fiber used for the test was a 200 μm core, NA=0.22 fiber, whereas the input fiber of the combiner has a specified NA of 0.15).

This device was also used to test the second loss calculation method. The results from the calculation performed with Eq. (7) on the data presented on figure 4 yielded the transfer function given on figure 5. The calculation was performed on every port, as illustrated in figure 5 (a), and the average was taken and extrapolated to 1 for low NA values in order to extrapolate the loss for different radiant intensity profiles. As we can see, light with $\mathrm{NA} \geq 0.22$ is completely blocked by the system as $T(0.22) \approx 0$. Figure 6 shows different measured radiant intensity distributions that will be used to extrapolate the total loss obtained for each source through the use of the transfer function $T(\mathrm{NA})$ and the formula of Eq. (8). The results of the calculation are grouped in table 1. The source at the test station is slightly overfilled (with $\mathrm{NA} \approx 0.16$ at 13.5%). The estimated loss, 12%, is thus close to the value obtained through the direct calculation method, as shown



(a) (b)

FIG. 4. Example of measurement performed on a 7×1 combiner with 200 μm core, NA=0.15 inputs and a 400 μm core, NA=0.22 output. (a) Average transmitted power and reference power as a function of filled NA at $1/e^2$ (≈13.5%) clip level ; (b) Average combiner transmission as a function of filled NA at $1/e^2$ clip level. The two theoretical loss curves shown in (b) are computed using the output fiber NA tolerance : the lower limit applies for NA=0.21 and the upper limit applies for NA=0.23. Also, source stability (in power and NA) combined with the delay between the measurements could have caused fluctuations in the input with respect to the reference curve. As we can see from (b), this combiner has a value of $\mathrm{BR} \geq 1$ and has a loss of about -0.3dB for an input filled NA of 0.15. This loss is believed to be caused mostly by brightness loss across the combiner. The input fiber used to launch in the combiner was a 200 μm core, NA=0.22 fiber. It can also be inferred from (a) that the input fiber guides light to an NA slightly higher than 0.15 since the transmission curve saturates at an NA above that value.

TAB. 1. Combiner loss for multiple radiant intensity distributions

	Test station	JDSU single-emitter	Alfalight single-emitter
Loss	12.1%	6.2%	3.8%

on figure 4 (about -0.5dB at NA=0.16). On the other hand, the commercial sources used for comparison have underfilled radiant intensity distributions, and thus, yield lower loss than the test station, as shown in table 1. The same holds true for the JDSU single-emitter, which has a slightly wider radiant intensity distribution than the Alfalight 808nm single-emitter and thus, is expected to exhibit more loss. Both the JDSU and Alfalight pumps are specified at NA=0.15.

5.2 19×1 design with BR<1

The device under analysis in this section is a 19×1 combiner with $\mathrm{BR} < 1$ consisting of 19 105 μm core, $\mathrm{NA} = 0.22$ inputs and a 200 μm core, $\mathrm{NA} = 0.46$ output. This device was designed to be operated with sources having an NA of about 0.20 (approximately 90% of the power confined in a cone of opening $\phi = \sin^{-1}(0.20)$.) Figure 7 shows both the NA calibration and transmitted power as a function of calibrated NA (respectively in subfigures (a) and (b)). The reference used to compute the direct loss calculation is the topmost curve on figure 7 (b). Calculations were performed using the method defined by Eq. (6) and the results are shown in figure 8. As we can see from the results of figure 8 (a) and (b), the combiner is expected to behave well, with low loss (around -0.4dB), up to the design input NA value of 0.20. On the other hand, operation with larger fill factors could be achieved, but the power handling of the device would have to be scaled accordingly from figure 8 in order to ensure adequate management of the excess loss (heat) by the high-power package.

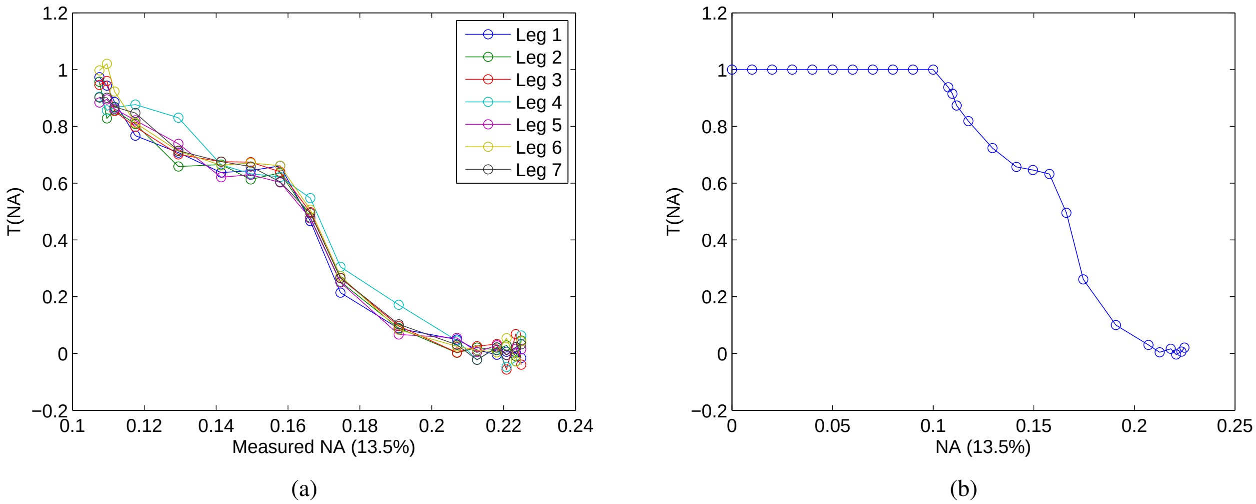


FIG. 5. $T(\mathrm{NA})$ transfer function calculated from Eq. (7) for the 7x1 combiner. (a) Calculated transfer function for every port in the available measured NA range ; (b) $T(\mathrm{NA})$ function averaged across all ports and extrapolated to unity for low NA values. It is presumed that low NA light passes losslessly through the combiner as is suggested by the low NA data points in (a). This transfer function can be used to estimate the loss of the combiner for any arbitrary angularly symmetric input radiant intensity distributions. The shoulder in $T(\mathrm{NA})$ around NA=0.15 is most probably due to the contribution of the loss induced by the leakage of the input fiber (specified at NA=0.15), which adds up to the effect of the combiner.

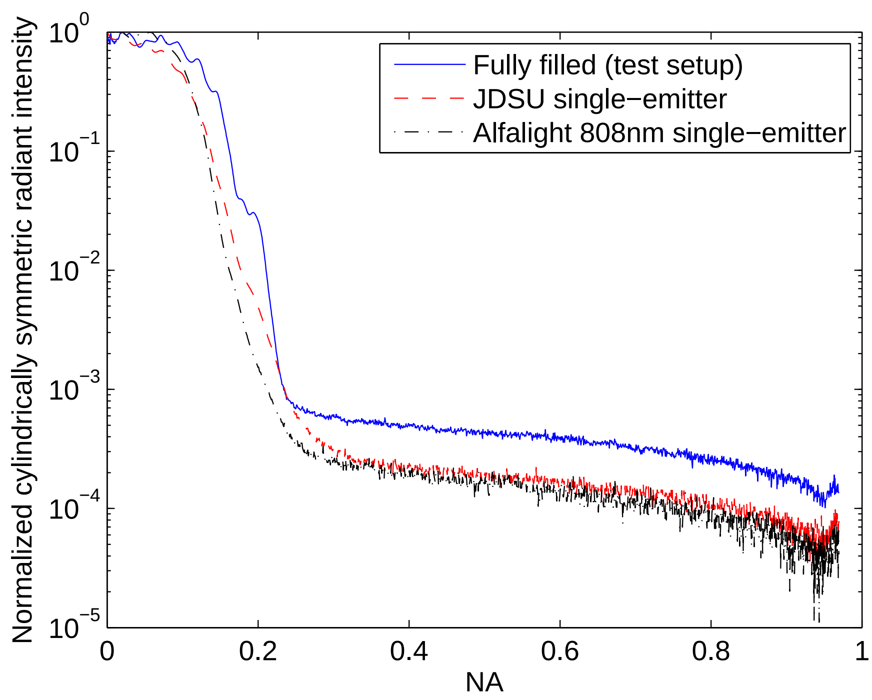
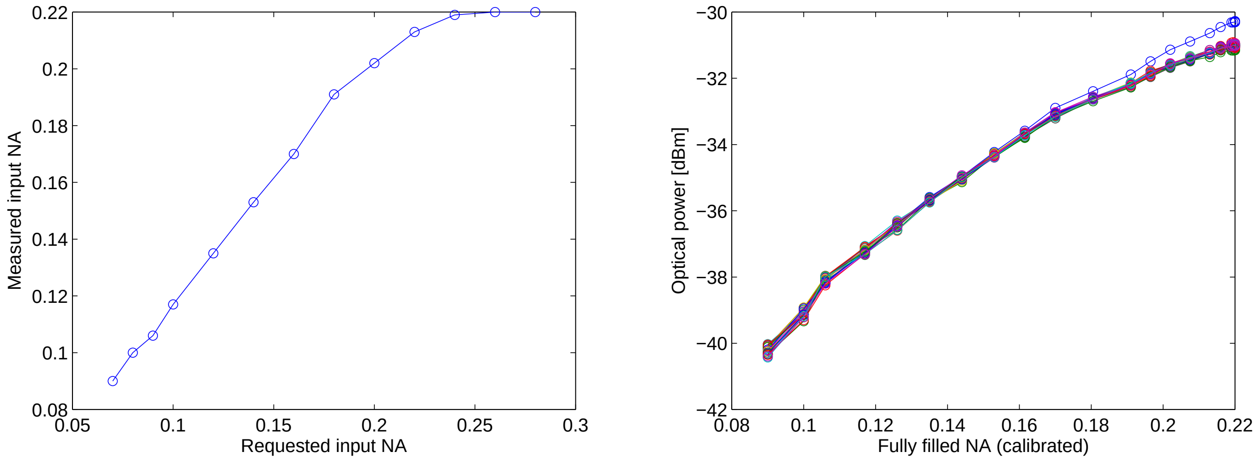
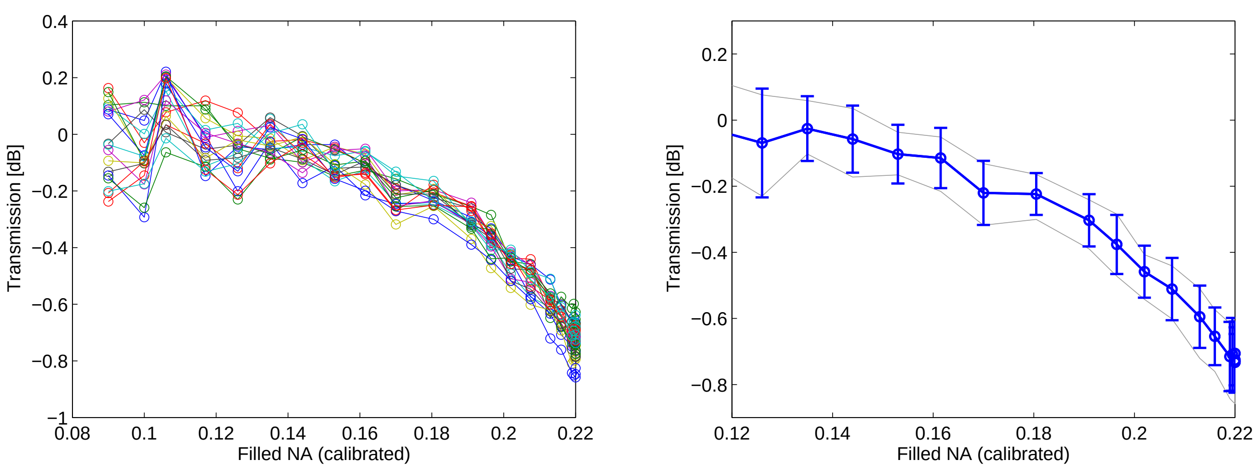


FIG. 6. Radiant intensity distributions of multiple sources used for loss estimation. As we can see, the radiant intensity distribution used at ITF is much closer to being fully-filled than the typical distributions of commercially available pump diodes. This is in responsible for the fact that ITF combiners seem to have lower loss than specified on product data report sheets when operated with typical single-emitter pump diodes.



(a) (b)

FIG. 7. Transmission measurement as a function of input filled far-field distribution. (a) Calibration of the filled input NA (measurement at 13.5% of maximum) ; (b) Direct measurement of power as a function calibrated NA. The topmost curve in (b) represents P_{in}, the power calibration curve at the input of the device.



(a) (b)

FIG. 8. Loss data for the 19x1 underfilled combiner as a function of input filled NA. (a) Loss as a function of NA for all ports, obtained from the data shown in figure 7 and calculated from Eq. (6) ; (b) Simplified loss as a function of NA showing the average, maximum and minimum values. The error bars represent twice the standard deviation across all ports calculated from the loss distribution over all ports illustrated in (a).

6. CONCLUSION

In this paper, we presented a new, innovative method to test the pump transmission of pump combiners and pump-and-signal combiners. This method involves the characterization of the transmission of the device as a function of input radiant intensity distribution. The input used for the presented evaluation is a "rectangular", angularly symmetric radiant intensity distribution with adjustable width, which we call a "filled" source. Use of such a source enables the direct calculation of loss versus NA of a given input for filled sources with corresponding NA. A second calculation method was also presented that allows to predict the loss of a device for any arbitrary radiant intensity distributions provided it is angularly symmetric. This powerful tool can therefore be used to perform a loss estimation for any commercially available source for any combiner. This method thus constitutes a very practical tool to help design low-loss, tight or underfilled devices (such as high-power combiners or splitters[3,4] with $\mathrm{BR} \leq 1$) for both fiber lasers and direct diode applications.

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