Fiber Coupled Diode Laser Beam Parameter Product Calculation and Rules for Optimized Design

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ABSTRACT

The Beam Parameter Product (BPP) of a passive, lossless system is a constant and cannot be improved upon but the beams may be reshaped for enhanced coupling performance. The function of the optical designer of fiber coupled diode lasers is to preserve the brightness of the diode sources while maximizing the coupling efficiency. In coupling diode laser power into fiber output, the symmetrical geometry of the fiber core makes it highly desirable to have symmetrical BPPs at the fiber input surface, but this is not always practical. It is therefore desirable to be able to know the 'diagonal' (fiber) BPP, using the BPPs of the fast and slow axes, **before** detailed design and simulation processes. A commonly used expression for this purpose, i.e. the square root of the sum of the squares of the BPPs in the fast and slow axes, has been found to consistently under-predict the fiber BPP (i.e. better beam quality is predicted than is actually achievable in practice). In this paper, using a simplified model, we provide the proof of the proper calculation of the diagonal (i.e. the fiber) BPP using BPPs of the fast and slow axes as input. Using the same simplified model, we also offer the proof that the fiber BPP can be shown to have a minimum (optimal) value for given diode BPPs and this optimized condition can be obtained before any detailed design and simulation are carried out. Measured and simulated data confirms satisfactory correlation between the BPPs of the diode and the predicted fiber BPP.

Keywords: diode laser fiber coupling, Beam Parameter Product, BPP, optimization

NOMENCLATURE

$d_{\perp}$	*Beam size, fast-axis*	Q_{sym}	*BPP, symmetrized*
$d_{=}$	*Beam size, slow-axis*	$\theta_{\perp}$	*Far-field divergence, fast-axis*
d_f	*Beam size, fiber core*	$\theta_{=}$	*Far-field divergence, slow-axis*
d_m	*Beam size, marginal ray*	θ_f	*Far-field divergence, fiber*
$Q_{\perp}$	*BPP, fast-axis*	θ_m	*Far-field divergence, marginal ray*
$Q_{=}$	*BPP, slow-axis*	θ_{sym}	*Far-field divergence, symmetrized*
Q_f	*BPP, fiber*	x	*BPP ratio*
Q_m	*BPP, marginal ray*	y	*Beam size ratio*
$Q_{dia,rms}$	*BPP, as defined in Equation (4)*		

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1. INTRODUCTION

In diode laser fiber coupled system design, designers are constantly striving to fit the output beam from the diodes to the fiber entrance with as little power loss as possible. The problem can be seen in Figure 1. The diode output beam which has a rectangular aperture and divergences in two orthogonal directions is being shaped by optical means in the 'beam shaping' portion and focused into the fiber entrance. In detailed optical design and simulation, a digital representation of the system is constructed and the laser power entering the fiber entrance is calculated as the performance indicator. However, in a product development cycle, it is often desirable to be able to estimate the fiber coupling performance for a given diode output before the detailed prediction is available. One situation that always happens is that the diode/stack configuration design comes much earlier in the design cycle than detailed optical design. Since the optical design changes with diode/stack configuration, it becomes uneconomical having to perform detailed optical design and simulation for every proposed diode/stack configuration in the effort of finding the optimal diode/stack configuration. A simplified calculation is used to evaluate proposed diode/stack designs before proceeding to detailed design on the chosen configuration.

The amount of light that can be coupled into the fiber is ultimately limited by the Beam Parameter Product (BPP) of the fiber. The definition of fiber BPP is given in Equation (1), refer to Figure (2).

$$Q_f = \frac{\theta_f}{2} \cdot \frac{d_f}{2} \quad (1)$$

For a laser beam to be captured by the fiber, its BPP has to be lower than the fiber BPP. On the other hand, at the diode output, the quality of the beam is given by the Beam Parameter Product (BPP) in two orthogonal directions (fast and slow axis) as defined in Equations (2) and (3).

$$Q_\perp = \frac{\theta_\perp}{2} \cdot \frac{d_\perp}{2} \qquad (2)$$

$$Q_= = \frac{\theta_=}{2} \cdot \frac{d_=}{2} \qquad (3)$$

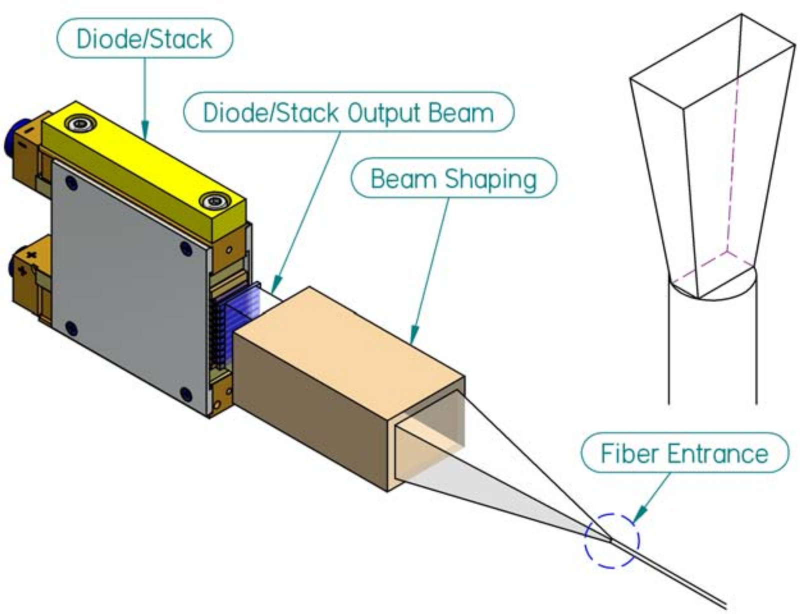

Figure 1. Laser Diode/Stack Fiber Coupling Design

It has long been established that BPPs are 'optical invariants' that can not be improved upon by optical systems. It is therefore obvious that the BPPs of the diode/stack would determine the best fiber BPP possible. For this purpose the following equation has been widely used:

$$Q_{dia,rms} = \sqrt{Q_{\perp}^2 + Q_{=}^2} \qquad (4)$$

Where $Q_{dia,rms}$ denotes the BPP of the beam from the diode in the diagonal direction. Previous literature states that for the fiber coupling to be efficient, $Q_{dia,rms}$ has to be smaller than the Q_f of the fiber. However, in our design process, we have found the diagonal BPP predicted by this equation had been consistently lower than could be eventually achieved. Also, we have not been able to find a proof for Equation (4) in published literature. In fact through a considerable period of time and many projects, our observation showed that the following equation provided much better correlation between the diode BPPs and the fiber BPP:

$$Q_{dia} = Q_{\perp} + Q_{=} \qquad (5)$$

It will be shown below that under certain simplifying assumptions, above Equation (5) is correct.

2. A SIMPLIFIED MODEL

Figure 2 illustrates a simplified model used in our proof. At the entrance of the fiber, we assume that:

a) The two-dimensional laser spot is a rectangle and

b) The divergences in the two directions are constants

It can be noted that these two assumptions imply that the laser beam has idealized 'clean' top-hat profiles that are rectangles in both physical space and divergence space. From this it can be seen that there exists four 'marginal rays' (corresponding to the corners of the rectangular laser spot) beyond which no laser energy exists. So if the fiber captures the 'marginal rays' at the corners, under this simplified model, 100% of the laser is coupled into the fiber. Hence assumption c) below:

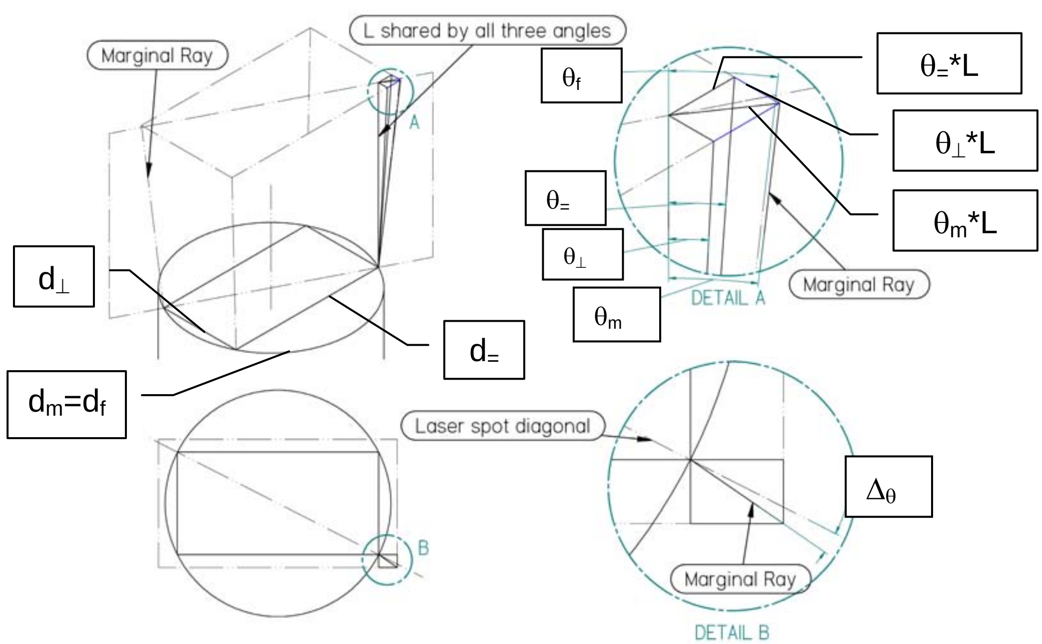

Figure 2. Simplified Model for Fiber Entrance

c) If the 'marginal ray' divergence is less or the same as that accepted by the fiber, all the laser light is captured, hence

$$\theta_m \le \theta_f \qquad (6)$$

Note the 'marginal ray' generally is not aligned with the fiber diameter defined by the rectangular laser spot, as shown by Δ_θ in 'Detail B' insert in Figure 2. However, this does not affect the validity of Equation (6).

As shown in Figure 2, both θ_m and d_m can be projected into two orthogonal directions ⊥ and = respectively. Noting the angles are small and the three angles $\theta_\perp$, $\theta_=$ and θ_m share a line segment L with arbitrary length gives the following:

$$\theta_m L = \sqrt{(\theta_\perp L)^2 + (\theta_= L)^2} \qquad (7)$$

Hence

$$\frac{\theta_m}{2} = \sqrt{\left(\frac{\theta_\perp}{2}\right)^2 + \left(\frac{\theta_=}{2}\right)^2} \qquad (8)$$

and

$$\frac{d_m}{2} = \sqrt{\left(\frac{d_\perp}{2}\right)^2 + \left(\frac{d_=}{2}\right)^2} \qquad (9)$$

The BPP of the 'marginal ray' is

$$Q_m = \frac{\theta_m}{2} \cdot \frac{d_m}{2} \qquad (10)$$

$$Q_m = \sqrt{\left(\frac{\theta_\perp}{2}\right)^2 + \left(\frac{\theta_=}{2}\right)^2} \cdot \frac{d_m}{2} \qquad (11)$$

Using Equations (2) and (3) and (9), above (11) can be rearranged into

$$\frac{Q_m}{Q_=} = \sqrt{\frac{\left(\frac{Q_\perp}{Q_=}\right)^2}{1-\left(\frac{d_=}{d_m}\right)^2} + \frac{1}{\left(\frac{d_=}{d_m}\right)^2}} \qquad (12)$$

Notice Equation (12) allows the calculation of the BPP of the 'marginal ray' from the diode BPPs and a parameter $\frac{d_=}{d_m}$.

Since the goal is to fit the 'marginal ray' into the fiber for given diode BPPs, it would be desirable to arrange $\frac{d_=}{d_m}$ so that Q_m becomes as small as possible.

3. MINIMIZATION OF DIAGONAL BPP

Assume

$$x = \frac{Q_\perp}{Q_=} \qquad (13)$$

and

$$y = \frac{d_=}{d_m} \qquad (14)$$

Equation (12) becomes

$$\frac{Q_m}{Q_=} = \sqrt{\frac{x^2}{1-y^2} + \frac{1}{y^2}} \qquad (15)$$

Because $Q_\perp$ and $Q_=$ are constant from the diode/stack, x will not change once the diode/stack configuration is chosen. Equation (15) shows the BPP of the 'marginal ray' is a function of y with a parameter x. Since the beam shaping design goal is $Q_m < Q_f$, if the right hand side (RHS) is minimized with respect of y, we can say the design will give the best Q_m for the given input diode BPPs. The conditions for obtaining a minimum of RHS of Equation (15) are as follow:

$$\frac{d}{dy}\left(\left. \sqrt{\frac{x^2}{1-y^2} + \frac{1}{y^2}} \right|_{x=c} \right) = 0 \qquad (16)$$

And

$$\frac{d^2}{dy^2}\left(\left. \sqrt{\frac{x^2}{1-y^2} + \frac{1}{y^2}} \right|_{x=c} \right) > 0 \qquad (17)$$

Detailed solution of above simultaneous equations is lengthy and omitted here but we have found the following expression satisfies equations (16) and (17):

$$y = \frac{1}{\sqrt{1+x}} \qquad (18)$$

Substituting Equation (18) into Equation (15) proves

$$\left. \frac{Q_m}{Q_=} \right|_{\min,\, x=c} = \left. \sqrt{\frac{x^2}{\left(1-y^2\right)} + \frac{1}{y^2}} \right|_{\min,\, x=c} = \left. \sqrt{\frac{x^2}{\left(1-y^2\right)} + \frac{1}{y^2}} \right|_{y=\frac{1}{\sqrt{1+x}}} = 1 + x \qquad (19)$$

The above minimization process is illustrated in Figure 3. The three-dimensional mesh and the contour on the x-y plane are the diagonal BPP function, Equation (15). The valley on the mesh is the minimum diagonal BPP for a specific x for which we have found a solution expressed in Equation (19) under the condition of Equation (18).

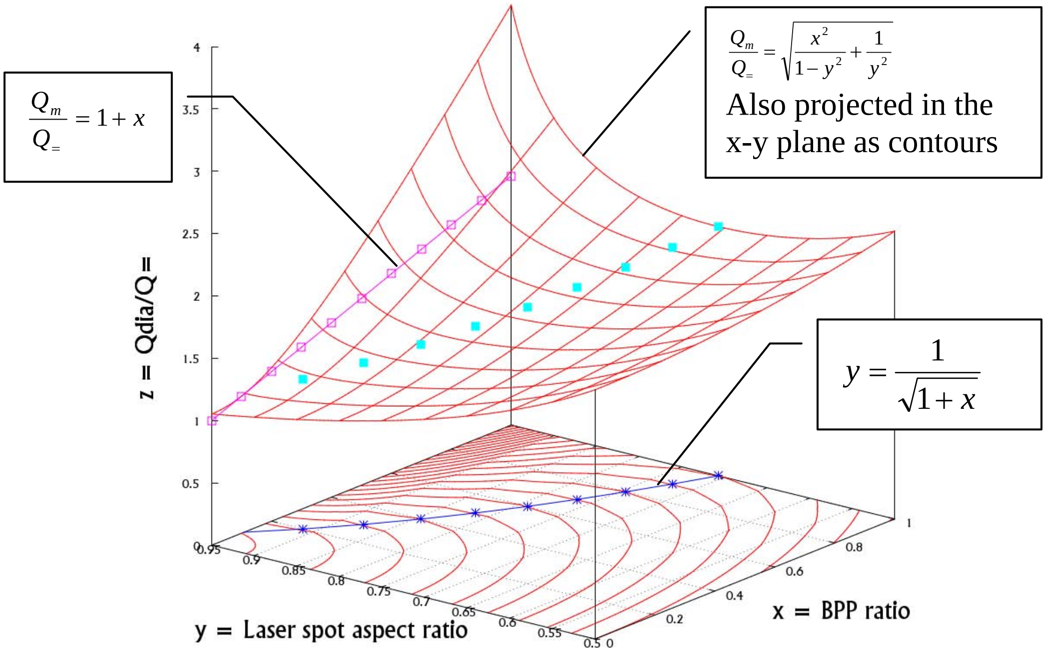

Figure 3 Minimization of diagonal BPP, Qm/Q=

Substituting definitions in Equations (13), (14), (2) and (3), Equation (18) implies

$$\frac{d_\perp}{d_=} = \sqrt{\frac{Q_\perp}{Q_=}} = \frac{\theta_\perp}{\theta_=} \qquad (20)$$

And Equation (19) implies

$$Q_m = Q_\perp + Q_= \qquad (21)$$

Keeping in mind the assumptions we have made in the above process, we can say Q_m in Equation (21) is the minimum possible value for Q_{dia}. To summarize, in addition to proving Equation (21), same as (5), is correct, we have also proven the sum of the two orthogonal BPPs is the ***minimum*** diagonal BPP possible, and to achieve this optimum, Equation (20) has to be satisfied.

4. ANALYSIS OF THE RESULT

Figure 4 compares the predicted diagonal BPPs based on the previously used Equation (4) and the new Equation (5) derived above. When x (the diode BPP ratio) is zero, the diode output is an idealized line source, i.e. BPP in one direction is zero, both equations predict, as expected, the 'diagonal' BPP the same as the non-zero BPP. Under all other conditions, the previously used RMS expression predicts considerably lower diagonal BPP than Equation (5). When x=1 (the right-most side of Figure 4), the condition corresponds to the 'symmetrized' configuration, i.e. the BPPs of both axes are equal. Under this configuration, the new formula predicts the diagonal BPP should be twice (2X) the value of the symmetrized BPPs (same in both directions, Q_{sym}) while the previous RMS expression, Equation (4), only predicts $\sqrt{2}$ times of the value. Under this condition, Equations (8) and (9) become the following:

$$\frac{\theta_m}{2} = \sqrt{2}\frac{\theta_{sym}}{2} \qquad (22)$$

and

$$\frac{d_m}{2} = \sqrt{2}\frac{d_{sym}}{2} \qquad (23)$$

Thus

$$Q_m = \frac{\theta_m}{2} * \frac{d_m}{2} = 2\frac{\theta_{sym}}{2} * \frac{d_{sym}}{2} = 2Q_{sym} \qquad (24)$$

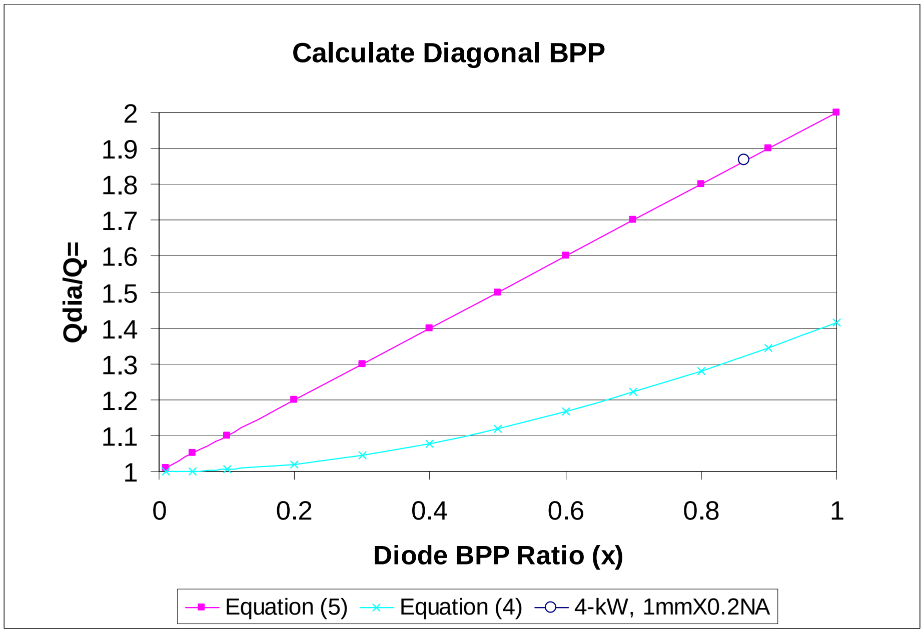

Figure 4. Prediction of the Diagonal BPP of a Diode Laser

Equation (24) is consistent with Equation (5). Because Equation (23) is obviously true, for the diagonal BPP to be $\sqrt{2}Q_{sym}$, as predicted by Equation (4), Equation (22) would have to become

$$\frac{\theta_m}{2} = \frac{\theta_{sym}}{2} \qquad (25)$$

This is clearly impossible. So the new expression gives a more sensible prediction under the 'symmetrized' configuration.

If the 'symmetrization' cannot be achieved, our solution shows an 'optimal' beam-shaping (minimum diagonal BPP) can still be achieved by making the output beam satisfy Equation (20). Under this condition, the diagonal BPP is given in

Equation (21). Inspection of Equation (20) shows under this condition, the ‘marginal’ ray is aligned in the direction of the diagonal of the laser spot, i.e. Δ_θ in Figure 2 is zero.

When Equation (20) cannot be satisfied, Equation (15) can be used to predict the ‘non-optimal’ diagonal BPP.

5. VALIDATION OF THE NEW FORMULA AND DESIGN FOR OPTIMIZED DIAGONAL BPP

Figure 5 shows the design parameters for a 4-kW, 1mmX0.2NA fiber coupled system, Ref [2]. The fast- and slow-axis BPPs (full width X full angle) are 216mm·mrad and 250mm·mrad respectively, and the fiber BPP is 400mm·mrad. Note in reality, assumptions a) and b) can never be completely true, so the BPPs are defined as ‘90% power included’. Equation (4) would have given the diagonal BPP as:

$$Q_{dia,rms} = \sqrt{216^2 + 250^2} = 330 mm \cdot mrad \qquad (26)$$

While Equation (21) predicts

$$Q_m = 216 + 250 = 466 mm \cdot mrad \qquad (27)$$

Equation (26) predicts we would have no trouble coupling 90% of the power into the fiber. However, the actual predicted BPP based on detailed design was 467mm·mrad (Figure 4). Beam conditioning device had to be placed before the focusing lens to reduce the beam BPP to a level acceptable to the fiber.

In Figure 5, each row represents a plane in the optical path and the beam-size, divergence and BPP in the three directions are tabulated. Parameters in the diagonal direction are calculated using Equations (8), (9) and (10). Row 1 shows the beam from the stacks. Row 2 to row 4 show the beams from the stacks being combined in various ways. In Row 5, the beam is expanded 5 times in the slow axis. Note the reduction in the diagonal BPP from 1130.5 to 467mm·mrad. The beam is then focused into the fiber by an f=165mm lens in Row 6. It is evident that the beam needs to be cleaned up before this step since the beam size is larger than 1mm. It should be noted that Row 1 through Row 6 is how beam shaping (in its simplest form) has been designed prior to the new method presented here. The main difference is, in the existing method (Row 5), the ‘5x expansion ratio’ is found in an iterative, trial-and-error process based on actual optical system designs, and in the new method (Row 7) the optimal condition (expansion ratio of 4.64) is explicitly solved from Equation (20), independent of any actual beam shaping design. Because of this advantage, the new method, Row 7 can be done at the earliest stages of the design and becomes the starting point of an optimized detailed design and simulation.

			Fast Axis			Slow axis			Diagonal		
Row Number	**Laser Beam Path (one-half of 4 stacks)**	**Nominal Power (W)**	**Beam size (mm)**	**Divergence (mrad) 90% power incl.**	**BPP (Full width x full angle)**	**Beam size (mm)**	**Divergence (mrad) 90% power incl.**	**BPP (Full width x full angle)**	**Beam size (mm)**	**Divergence (mrad) 90% power incl.**	**BPP (Full width x full angle)**
1	Single Stack (with FAC and SAC lens)	600	21.6	5	108	10	25	250	23.8	25.5	606.8
2	After interleaving 2 stacks (2xpower of a single stack)	1200	21.6	5	108	10	25	250	23.8	25.5	606.8
3	After PBC of 2 pairs of interleaved stacks (4xpower of single stack)	2400	21.6	5	108	10	25	250	23.8	25.5	606.8
4	**After optical stacking of the second half of 4 stacks**	4800	43.2	5	**216**	10	25	**250**	44.3	25.5	1130.5
5	5x expansion in Slow Axis	4800	43.2	5	**216**	50	5	**250**	66.1	7.1	467.2
6	after f=165mm focusing lens	4800							1.16	400.6	467.2
7	4.64x expansion in Slow Axis (Optimized for Diagonal BPP)	4800	43.2	5	**216**	46.4	5.39	**250**	63.4	7.4	466.0

Figure 5. Design parameter of a 4-kW, 1mmX0.2NA fiber coupled turn-key system. Courtesy of authors of Ref [2]

6. CONCLUSIONS

The result presented here proved that the optimal fiber input BPP is the sum of the BPPs in the two orthogonal directions of the diode/stack, Equation (21) and the condition at which this optimal is obtained is when ratio of the spot sizes equals to that of the divergences, Equation (20). If the optimum could not be attained, Equation (15) or (12) can be used to calculate the diagonal BPP.

The advantages of the calculation presented here are:

- The BPP of the diagonal can be calculated prior to any detailed design and simulation. This offers practical benefits in both conceptual design and quoting phases.
- For a design that cannot be completely symmetrized, the formula presented here provides valuable insights and a good starting design point which is optimized for having minimal diagonal BPP.
- Compared with a previously used formula, the new expression compares favorably in both simulation and test result.

7. ACKNOWLEDGEMENT

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