Simulation Study on Optically Designed Refractive Beam Expander for Nd: YAG Laser Harmonics for 7 Km Detection Range

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Abstract:

The simulation study has been conducted for the harmonics of Nd: YAG laser, namely the second harmonic generation SHG, the third harmonic generation THG, and the fourth harmonic generation FHG. Determination of beam expander's expansion ratio for specific wavelength and given detection range is the key in beam expander design for determining minimum laser spot size at the target. Knowing optimum expansion ratio decreases receiving unit dimensions and increases its performance efficiency. Simulation of the above mentioned parameters is conducted for the two types of refractive beam expander, Keplerian and Galilean. Ideal refractive indices for the lenses are chosen adequately for Nd: YAG laser harmonics wavelengths, so that increasing transmission of laser beam, consequently the received power to the detector for practical convenience.

Key words: Beam Expander, Laser, Spot Size, Expansion Ratio, Galilean, Keplerian.

Introduction:

Some applications require a laser beam with low divergence angle, θ.Reducing θ requires expanding waist of laser beam in question. This could be achieved by applying a beam expander. Generally, a beam expander consists of two lenses. Firstly, the beam is diverged with a short focal length lens and secondly, the diverged beam is re-collimated with a longer focal length hence, larger beam waist and smaller divergence. The lenses are positioned like an inverted telescope [1]. See figure (1).

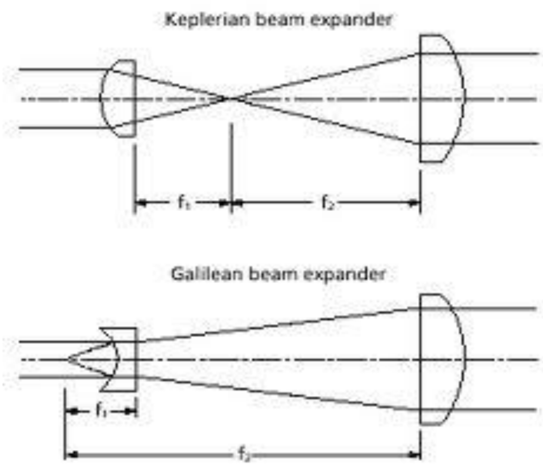

Fig. (1) shows beam expander design, the upper is Keplerian type and the lower is Galilean type.

Mathematical Relations of Beam Expander Design

Power flux, I_o, at laser source is given as [2]:

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$I_o = \frac{4P}{\pi w_o^2}$ ………… (1)

Where W_o is laser beam diameter in millimeter, P is transmitting peak power in Watt, which is given as:

$P = \frac{E_{laser}}{\tau_{laser}}$ ……………..… (2)

Where E_{laser} is energy of laser radiation in Joule, τ_{laser} is laser pulse width in nanosecond.

For a target at range R, diameter of laser beam at target's surface is:

$$W(R) = W_o \sqrt{1 + \left(\frac{\lambda R}{\pi (\frac{W_o}{2})^2}\right)^2} \quad \text{…… (3)}$$

Where λ is laser radiation wavelength in nanometer.

Laser power flux at target's surface is given as:

$I(T) = \frac{P \tau_a \tau_{to}}{\Omega(t) R^2}$ ………. (4)

Where τ_a is atmospheric transmittance which is given as:

$\tau_a = e^{-\sigma_\lambda R}$ ……….(5)

where σ_λ is spectral coefficient of attenuation of laser radiation which is in Km^{-1}.

τ_{to} is transmittance of transmitting lenses.

Ω (t) is transmitting solid angle which is given in Stredian.

Fixed beam expander is composed of, i.e. two positive lenses or one positive and the other is negative, at least with different focal lengths and diameters .The first lens is denoted by L_1, and its diameter is D_1. D_1 should meet the condition:

$D_1 \geq 2 W_o$ .... (6)

And its focal length is F_1. Generally, F – number, F #, which is a measure of radiation gathering power of optical system, is given as [3]:

$F\# = F_1 / D_1$ …… (7)

Where F_1, D_1 are focal length and diameter of the first lens, respectively. Combining Eqs. (6) and (7), and solving for F_1, yields:

$F_1 \geq 2 W_o F\#$ …… (8)

The second lens is denoted by L_2, and the lens diameter is D_2, and its focal length is F_2. .Expansion ratio, or magnification factor, of beam expander $\aleph$, is given by [4]:

$$\aleph = \frac{F_2}{F_1} = \frac{D_2}{D_1} = \frac{\theta_1}{\theta_2} \quad \text{…… (9)}$$

Where θ_1, θ_2 are laser beam divergence of first and second lenses, respectively, Solving Eq. (9) for F_2, yields:

$F_2 \geq \aleph F_1$ …… (10)

$D_2 \geq \aleph D_1$ …… (11)

So, Beam Expander Length, BEL**,** is given as:

$BEL \geq F_1 + F_2$ …….. (12)

Or

$BEL \geq 2 W_o F\# (1 + \aleph)$ ……. (13)

Laser spot diameter will be decreased according to the following equation:

$$W(R) = W_o \aleph \sqrt{1 + \left(\frac{\lambda R}{\pi (\frac{\aleph W_o}{2})^2}\right)^2} \quad \text{…. (14)}$$

Methodology

To increase laser intensity at a range R, without increasing initial laser power, laser beam divergence should be decreased. Decreasing divergence leads to a smaller laser spot diameter at range R, hence a higher intensity is reflected from the target in question. Decreasing laser divergence could be done by increasing expansion ratio, $\aleph$ of laser beam by applying beam expander to the transmitting unit. Choosing optimum $\aleph$ leads to minimum dimensions for transmitting and receiving units. Optimum $\aleph$ could be obtained by plotting expansion ratios for a specific laser versus spot laser beam diameter for a specific range; the bottom of the graph represents the optimum value of expansion ratio. The optimum expansion ratios are deduced from Eq. (14), see figure (2).

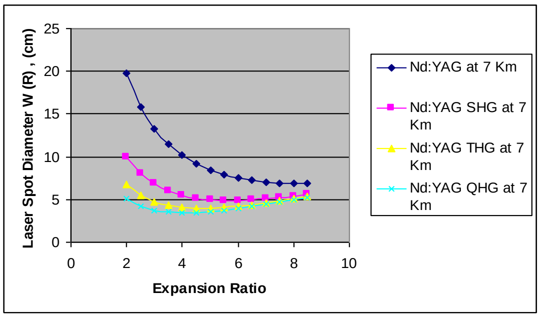

Fig. (2) shows simulated expansion ratios values versus laser spot diameters for Nd: YAG harmonics at 7 Km detection range.

Simulated Result Data

Laser spot diameter optimum reduction as beam expander is applied for different wavelengths for certain range as shown in next table.

Table (1) specifies simulated values of laser spot diameters and optimum expansion ratios at 7 Km detection range before and after applying beam expander to Nd: YAG laser harmonics, Eq. (3) and Eq. (14) respectively. The initial laser beam diameter is 6 mm.

Laser Type	Wavelength (nm)	W(R) Before Expansion (cm)	Expansion Ratio at 7 Km	W(R) After Expansion (cm)
Nd:YAG	1064	39.5	7X	7.033
SHG, Nd:YAG	532	19.65	5X	4.95
THG, Nd:YAG	355	13.19	4X	4.07
FHG, Nd:YAG	266	9.89	3.5X	3.51

Inner and outer lens diameter beside their divergences and material as a function to applied laser wavelengths for certain range as shown in the next table.

Table (2) specifies simulated values of laser beam expander lenses diameters, D_1 Eq. (6), D_2 Eq. (11) and final laser beam divergence Eq. (9) at 7 Km detection range for Nd: YAG laser harmonics. Initial laser beam divergence is θ_1=10 mrad.

Laser Type	Wavelength (nm)	Expansion Ratio at 7 Km	D_1 (cm)	D_2 (cm)	Divergence (mrad)	Lens Material
Nd:YAG	1064	7X	1.2	10	1.428	BK-7
SHG, Nd:YAG	532	5X	1.2	7.6	2.0	BK-7
THG, Nd:YAG	355	4X	1.2	6.4	2.5	MgF_2
FHG, Nd:YAG	266	3.5X	1.2	5.8	2.85	MgF_2

First and second lens focal lengths, beam expander length and their field of views are shown in the next table as a function of beam expander type for λ = 1064 nm.

Table (3) shows beam expander types against focal lengths of inner Eq. (8) and outer lenses Eq. (10) beside its length Eq. (12) and field of view for Nd: YAG laser, λ = 1064 nm at 7 Km range.

Beam Expander Type	Lens Type	1^{st} Lens Focal Length (cm)	2^{nd} Lens Focal Length (cm)	Beam Expander Length (cm)	Field of View (mrad)
Keplerian	Biconvex	4.93	34.51	39.44	242.61
	Planoconvex	9.86	69.03	78.89	121.53
Galilean	Biconcave	-4.93	34.51	29.58	242.61
	Planoconcave	-9.86	69.03	59.17	121.53

First and second lens focal lengths, beam expander length and their field of views are shown in the next table as a function of beam expander type for λ = 532 nm.

Table (4) shows beam expander types against focal lengths of inner Eq. (8) and outer lenses Eq. (10) beside its length Eq.(12) and field of view for SHG, Nd: YAG laser, λ = 532 nm at 7 Km range.

Beam Expander Type	Lens Type	1^{st} Lens Focal Length (cm)	2^{nd} Lens Focal Length (cm)	Beam Expander Length (cm)	Field of View (mrad)
Keplerian	Biconvex	4.85	24.27	29.126	245.95
	Planoconvex	9.7	48.54	58.25	123.44
Galilean	Biconcave	-4.85	24.27	19.41	245.95
	Planoconcave	-9.7	48.54	38.83	123.44

First and second lens focal lengths, beam expander length and their field of views are shown in the next table as a function of beam expander type for λ = 355 nm.

Table (5) shows beam expander types against focal lengths of inner and outer lenses beside its length and field of view for THG, Nd: YAG laser, λ = 355 nm at 7 Km range.

Beam Expander Type	Lens Type	1^{st} Lens Focal Length (cm)	2^{nd} Lens Focal Length (cm)	Beam Expander Length (cm)	Field of View (mrad)
Keplerian	Biconvex	6.09	24.39	30.48	196.16
	Planoconvex	12.19	48.78	60.97	983.2
Galilean	Biconcave	-6.09	24.39	18.29	196.16
	Planoconcave	-12.19	48.78	36.58	983.2

First and second lens focal lengths, beam expander length and their field of views are shown in the next table as a function of beam expander type for λ = 266 nm.

Table (6) shows beam expander types against focal lengths of inner and outer lenses beside its length and field of view for THG, Nd: YAG laser, λ = 266 nm at 7 Km range.

Beam Expander Type	Lens Type	1st Lens Focal Length (cm)	2nd Lens Focal Length (cm)	Beam Expander Length (cm)	Field of View (mrad)
Keplerian	Biconvex	5.95	20.83	26.78	200.92
	Plano convex	11.9	41.66	53.57	100.71
Galilean	Biconcave	-5.95	20.83	14.88	200.92
	Planoconcave	-11.9	41.66	29.76	100.71

Conclusion

Plotting a graph of expansion ratio versus laser spot diameter for given range determines the optimum expansion ratio of each wavelength of Nd: YAG laser harmonics. This determination led to determine how smaller the laser spot diameter will be, hence specifying beam expander lenses diameters , its focal lengths and final beam divergence for each wavelength. Knowing the laser wavelength led to specify lens material which has highest transmission curve. The following results are obtained:

- Minimum laser spot diameter without beam expander is for shortest wavelength of Nd: YAG harmonics namely, FHG, Nd: YAG at 7 Km detection range.
- Optimum ℵ is obtained by plotting expansion ratio values for specific laser versus spot laser beam diameter for a specific range; the bottom of the graph represents the optimum value.
- Required minimum laser expansion ratio is for shortest wavelength namely, FHG, Nd: YAG at 7 Km detection range.
- Biconcave Galilean beam expander length is the minimum for any range comparing with other types and the most minimum for the shortest wavelength namely 266 nm.
- Field of view of Plano convex and Plano concave of 266 nm wavelength is the most minimum.

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دراسة محاكاه لتصميم موسع الحزمة الكاسر لتوافقيات ليزر النميديوم ياك لمدى كشف سبعة كيلومتر

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الخلاصة:
تم إجراء دراسة المحاكاة على التوافقيات الثلاثة لليزر النميديوم ياك، و يقصد بها تولد التوافقي الثاني، و تولد التوافقي الثالث ،و تولد التوافقي الرابع. إن تحديد نسبة التوسيع لطول موجي و مدى كشف محدد يلعب دورا في تصميم موسع حزمة ذو مواصفات تكوين أوطئ مساحة بقعة ليزرية عند الهدف.إن معرفة نسبة التوسيع المثلى يقلل من إبعاد وحدة الاستلام الليزرية مع احتفاظها بكفاءة أدائها. كذلك أجريت دراسة المحاكاة على معاملات تصميم موسع الحزمة على نوعيه المعروفين الكبلري و الكاليلي. تم اختيار معاملات الانكسار المناسبة للعدسات ذات اعلي نفاذية لتأمين قدرة كشف عند وحدة الاستلام. و للموائمة العملية أجريت الدراسة على أنواع العدسات المختلفة لتبيان الأثر على طول موسع الحزمة.