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Excitation Efficiency with Respect to the Spot Size in case of Laser Diode in Visible Spectrum to Mono-Mode Parabolic Core Fiber; Upside Down Tapered Hyperbolic Micro Lens Drawn on the Tip of the Fiber

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Abstract *-This paper is based on theoretical investigation of the coupling optics of laser diode using visible spectrum to a circular core single mode fiber excitation via an upside down tapered hyperbolic micro lens on the tip of the fiber. In this context, ABCD matrix formalism employed for prediction of concerned excitation efficiency. The concerned estimation requires computation with relevant programming. The analysis will be extremely useful for the design of suitable upside down tapered hyperbolic micro lens on the tip of the fiber from the point of view of optimum launch optics. Further, the formalism developed is user friendly in terms of execution and therefore it would be profiteering for the engineers who are active in the domain of all optical communication of information. And specially from Illumination engineering point of view using visible light would be very much cost effective in this regard considering its bounty availability and since its pretty easy to generate in industrial environment. This is actually Excitation efficiency in case laser diode in visible spectrum to mono-mode parabolic core fiber via upside down tapered micro lens drawn on the tip of the fiber.*

Index Terms - Mono-mode parabolic core fiber, Laser diode, Visible spectrum.

I. **INTRODUCTION** - Single-mode optical fiber has emerged as the most efficient medium in the field of optical communication. For the purpose of maximizing source to fiber excitation efficiency, micro lenses of different designs are being fabricated and reported as well. These micro lenses which are fabricated either in the hemispherical or conical shape possesses self centering characteristics. It is well known facts that the photometric range of a standard human eye is 380-830nm[7]. This is why, here the operating wavelength is restricted between

720nm to 830 nm in order to obtain minimum attenuation loss. Although easily fabric able but slightly less efficient hemispherical micro lens on the fiber tip is used widely, the hyperbolic micro lens on the fiber tip has been found to most efficient coupler. Side by side, in the field of coupling optics, fabrication of upside down tapered lens in optical fiber is receiving considerable attention. ABCD matrix treatment has been widely used in

analyzing and designing different types of micro lenses on the fiber tip as far as coupling of a laser diode with optical fiber is concerned. It has been reported that ABCD matrix formalism predicts the coupling optics involving micro lens on the fiber tip accurately but in a simple fashion. By using ABCD matrix formalism, laser diode to fiber excitation efficiency in case of upside down tapered lens step index optical fiber has also been predicted in a simple manner with sufficient accuracy. This adequate accuracy coupled with simplicity of

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ABCD matrix formalism[8] motivated us to employ this simple formalism to predict the coupling optics involving upside down tapered hyperbolic lens drawn on parabolic index fiber. It is very relevant to mention in this connection that the importance of parabolic index fiber has been already established in the field of optical communication on account of its large bandwidth and negligible sensitivity to micro and macro bending.[18] Accordingly, the investigation on optimum launch optics involving graded index fiber is proliferating in literature. In this report the wavelength restricted range is in visible spectrum, in order to predict the coupling optics, similar to previous research workers, employed the Gaussian[13] field distributions applied for both the laser source and the fiber. Analytical expressions for the relevant coupling optics are formulated and the concerned calculations require little computation. The results found here will predict the most coupling effective upside down tapered lens in parabolic index optical fiber with respect to the particular wavelength used. Further, the present study involves prediction of tolerance sensitivity of the coupling device with respect to transverse and angular mismatches for both the wavelengths used. The present formalism will ease the designers and packagers who are engrossed in the domain of optical technology.

II. THEORY

The coupling device has been diagrammatically presented in Fig.1. Here n1 and n2 represent the refractive indices of incident and lens media respectively. The intensity profile of laser diode emitted by optical beam is approximated in terms of Gaussian spot sizes w1x and w1y along with two mutually perpendicular directions x and y, with x and y being parallel and perpendicular respectively to the junction plane[6].The laser diode field at a distance u from the lens surface is denoted as Ψ_u which is approximated as:

$$\Psi_u = \exp[-(\frac{x^2}{w_{1x}^2}+\frac{y^2}{w_{1y}^2})]\times\exp[-\frac{jk_1(x^2+y^2)}{2R_1}] \quad (1)$$

Here, w1x and w1y represent the spot sizes along the two mutually orthogonal directions X and Y[6]. The radius of curvature of the incident wave front has been denoted by R1 and the wave number in incident medium has been indicated as k1[6]. It has been already reported that Gaussian approximations for the fundamental mode in the circular core single-mode fiber represent coupling optics with sufficient accuracy[13]. Accordingly, similar expression for fundamental mode was used of the fiber as expressed below,

$$\Psi_f = \exp[-\frac{(x^2+y^2)}{w_f^2}] \quad (2)$$

where, wf represents the fiber spot size[17].

Further, the polarization match of the laser field with the mode of circular core single-mode fiber is also imperative in this context. The upside down tapered hyperbolic lens transformed laser field Ψ_v fiber plane 2 is expressed as:

$$\Psi_v = \exp[-(\frac{x^2}{w_{2x}^2}+\frac{y^2}{w_{2y}^2})]\times\exp[-\frac{jk_2}{2}(\frac{x^2}{R_{2x}}+\frac{y^2}{R_{2y}})]$$

(3)[6]

where, k2 stands for the wave number in the lens medium.

The transformed spot sizes and the corresponding radii of curvature in x and y directions respectively are designated as w2x, w2y and R2x, R2y[6][18]. This has shown, in the appendix, the evaluation method of w2x,2y and R2x,2y in terms of w1x,1y and R1 by the ABCD matrix[6]. Again, laser diode to single-mode parabolic index fiber coupling efficiency via upside down tapered lens is obtained by using the following overlap integral:

$$\eta = \frac{|\iint \Psi_v \Psi_f^* \, dxdy|^2}{|\iint |\Psi_v|^2 dxdy \iint |\Psi_f|^2 dxdy|} \quad (4)[9]$$

Using Equations (2) and (3) in Equation (4), we obtain

$$\eta = \frac{4w_{2x}\, w_{2y}\, w_f^2}{([(w_f^2+w_{2x}^2)^2+\frac{(k_2^2 w_f^4 w_{2x}^4)}{(4R_{2x}^2)}]^{0.5}\times[(w_f^2+w_{2y}^2)^2+\frac{(k_2^2 w_f^4 w_{2y}^4)}{(4R_{2y}^2)}]^{0.5})}$$

(5)[6]

The distribution of refractive index for graded index fiber of arbitrary profile exponent (g) is given by,

$$n(r) = n_{c0}[1-2(\frac{r}{a_0})^g \Delta]^{0.5} \; for \; r < a_0 \quad (6\text{-}a)$$

$$n(r) = n_d = n_{c0}[1-2*\Delta]^{0.5} \; for \; r \geq a_0 \quad (6\text{-}b)$$

Where Δ represents the grading parameter, which is denoted by,

$$\Delta = \frac{n_{co}^2}{2n_{co}^2} - \frac{n_{cl}^2}{2n_{co}^2} \quad (7)[19]$$

It deserves mentioning in this context that g =1, 2 and ∞ correspond to refractive index distribution in terms of triangular, parabolic and step profiles respectively. The Gaussian spot size w_f for graded index fiber can be approximated as:

$$\frac{w_f}{a_0} = \left[\frac{A'}{V^{2/(g+2)}} + \frac{B'}{V^{3/2}} + \frac{C'}{V^6}\right] \quad (8)$$

The constants A', B' and C' are evaluated by applying parameter optimization technique .The values found are as follows (1.5<V<∞).

$$A' == [2/5\{1 + 4\left(\frac{2}{g}\right)^{\frac{5}{6}}\}]^{\frac{1}{2}} \quad (9.a)$$

$$B' = e^{0.298/g} - 1 + 1.478(1 - e^{-0.077g}) \quad (9.b)$$

$$C' = 3.76 + \exp(4.19/g^{0.418}) \quad (9.c)$$

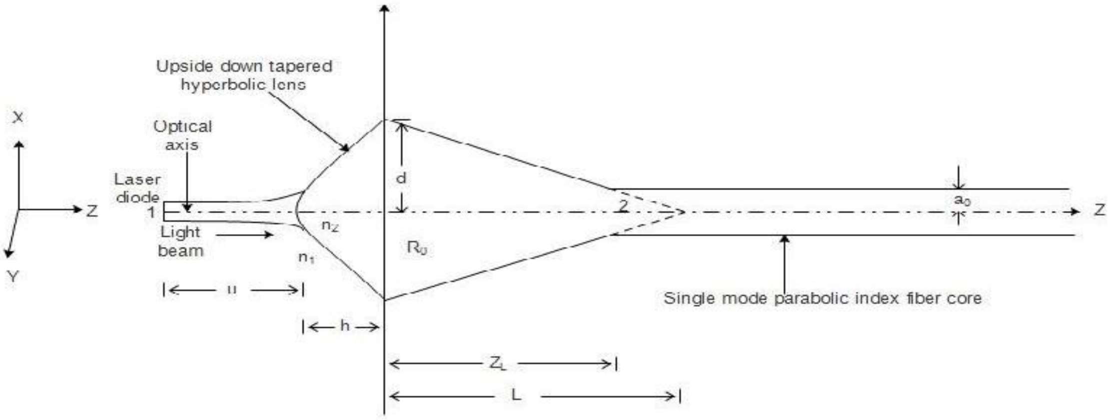

Fig.1: Schematic diagram of light beam emitted from the input plane 1 of a laser diode and refracted through upside down tapered hyperbolic micro lens into plane 2 which is the end face of a circular core single-mode parabolic index

III.RESULT AND DISCUSSION :

For estimation of coupling optics involving laser diode and upside down tapered hyperbolic micro lens drawn from the end of a parabolic index circular core fiber, here, some laser diode has emitting wavelength 725 nanometer to 830 nanometer.Additionally,as to this topic, the refractive index of the material of micro lens with respect to incident medium is considered as 1.46 .We choose the relevant parameters namely core radius (a0) which is fixed at 4 micrometer and change the radius of aperture (d) between 3 micro meter and 6 micro meter. Further, here the upside down taper length (zL) drawn from the end of the fiber is 26.6 micro meter corresponding to the taper length (L) measured from its geometrical vertex being 80 micro meter. Again, in this case axial refractive index of core as 1.46 was used while that for cladding as 1.45. Further, it has been shown that prediction of coupling optics based on planar wave front model for the incident beam from the laser diode differs negligibly from that based on spherical wave front model. Accordingly, for the sake of simplicity along with accuracy, planar wave front model for the present investigation were used. Here, a upside down parabolic index fibers has taken, having spotsizes (wf) are 3.019,3.57,4.000,4.57,5.006,5.578 and 6.156 micro meter. It is observed that we get 100% coupling efficiency with the corresponding separation (u) between laser diode and microlens for the spot size of 3.57 micro meter in the specific range of wavelength which is 730nm to 735nm.We also observed that whenever we increase the spot size and kept the core radius fixed at 4 micrometer and radius of aperture fixed at 3 micrometer then the higher coupling efficiency will shift in higher region of wavelength and when we change the radius of aperture in 6 micrometer and kept rest of the parameters remain unchanged then higher coupling efficiencies takes place in lower region of wavelength. Mainly when core radius is 4 micro meter, radius of aperture is fixed at 6 micro meter then at spot size 5.578 micro meter we observed that coupling efficiency is 100% with the corresponding separation (u) between laser diode and microlens in the wavelength range of 740 - 750nano meter. The following data tables consist of all the obtained data and the attached graphs shown the highest efficiencies with respect to the wavelengths.

Table: 1

Core radius (in micro meter): a=4

Radius of aperture (in micro meter): d=3

wavelengths	Spotsize:3.019	Spotsize:3.57	Spotsize:4.000	Spotsize:4.57	Spotsize:5.006	Spotsize:5.578	Spotsize:6.156
725nm	0.9803	0.9999	0.9863	0.9417	0.8955	0.8275	0.7573
730nm	0.9785	1.0000	0.9878	0.9448	0.8994	0.8368	0.7624
735nm	0.9766	1.0000	0.9892	0.9477	0.9032	0.8322	0.7674
740nm	0.9747	0.9999	0.9905	0.9506	0.9069	0.8414	0.7724
745nm	0.9727	0.9997	0.9918	0.9534	0.9106	0.8458	0.7773
750nm	0.9706	0.9995	0.9929	0.9561	0.9142	0.8502	0.7822
755nm	0.9685	0.9992	0.9939	0.9586	0.9177	0.8545	0.7870
760nm	0.9664	0.9988	0.9949	0.9611	0.9211	0.8588	0.7918
765nm	0.9642	0.9983	0.9958	0.9636	0.9244	0.8630	0.7965
770nm	0.9620	0.9977	0.9966	0.9636	0.9277	0.8671	0.8011
775nm	0.9597	0.9971	0.9973	0.9681	0.9308	0.8711	0.8057
780nm	0.9574	0.9964	0.9979	0.9703	0.9339	0.8751	0.8102
785nm	0.9550	0.9956	0.9984	0.9723	0.9369	0.8790	0.8147
790nm	0.9526	0.9948	0.9989	0.9743	0.9398	0.8829	0.8191
795nm	0.9501	0.9938	0.9992	0.9762	0.9427	0.8866	0.8232
800nm	0.9477	0.9929	0.9995	0.9781	0.9455	0.8903	0.8278
805nm	0.9452	0.9918	0.9998	0.9798	0.9482	0.8939	0.8320
810nm	0.9426	0.9907	0.9999	0.9815	0.9505	0.8975	0.8362
815nm	0.9400	0.9934	1.0000	0.9830	0.9533	0.9010	0.8404
820nm	0.9374	0.9884	1.0000	0.9846	0.9558	0.9044	0.8444
825nm	0.9348	0.9871	0.9999	0.9860	0.9582	0.9077	0.8484
830nm	0.9321	0.9858	0.9998	0.9873	0.9605	0.9110	0.8524

Table: 2

Core radius (in micro meter);;a=4

Radius of aperture (in micro meter);;d=6

wavelengths	Spotsize:3.019	Spotsize:3.57	Spotsize:4.000	Spotsize:4.57	Spotsize:5.006	Spotsize:5.578	Spotsize:6.156
725nm	0.7374	0.8494	0.9151	0.9717	0.9936	0.9993	0.9846
730nm	0.7325	0.8450	0.9115	0.9694	0.9925	0.9997	0.9862
735nm	0.7275	0.8406	0.9078	0.9671	0.9913	0.9999	0.9877
740nm	0.7226	0.8361	0.9041	0.9647	0.9900	1.0000	0.9892
745nm	0.7177	0.8316	0.9004	0.9622	0.9886	1.0000	0.9905
750nm	0.7129	0.8722	0.3966	0.9597	0.9872	1.0000	0.9918
755nm	0.7080	0.8227	0.3928	0.9571	0.9856	0.9998	0.9929
760nm	0.7032	0.8182	0.3890	0.9545	0.9840	0.9995	0.9940
765nm	0.6984	0.8137	0.3851	0.9518	0.9824	0.9992	0.9949
770nm	0.6937	0.8093	0.3813	0.9491	0.9807	0.9988	0.9958
775nm	0.6890	0.8048	0.3774	0.9463	0.9789	0.9983	0.9966
780nm	0.6843	0.8003	0.3735	0.9435	0.9770	0.9978	0.9973
785nm	0.6796	0.7959	0.3695	0.9406	0.9751	0.9971	0.9979
790nm	0.6750	0.7914	0.3656	0.9377	0.9731	0.9964	0.9985
795nm	0.6704	0.7870	0.3617	0.9348	0.9711	0.9956	0.9989
800nm	0.6658	0.7826	0.3577	0.9318	0.9690	0.9948	0.9993
805nm	0.6613	0.7781	0.3537	0.9287	0.9669	0.9938	0.9996
810nm	0.6568	0.7737	0.3497	0.9257	0.9647	0.9928	0.9998
815nm	0.6523	0.7693	0.3457	0.9226	0.9624	0.9918	0.9999
820nm	0.6479	0.7649	0.3417	0.9195	0.9601	0.9906	1.0000
825nm	0.6435	0.7605	0.3377	0.9163	0.9578	0.9894	1.0000
830nm	0.6391	0.7562	0.3337	0.9131	0.9554	0.9882	0.9999

Fig 2:Plot of highest coupling efficiency with corresponding wavelengths with respect to spot size

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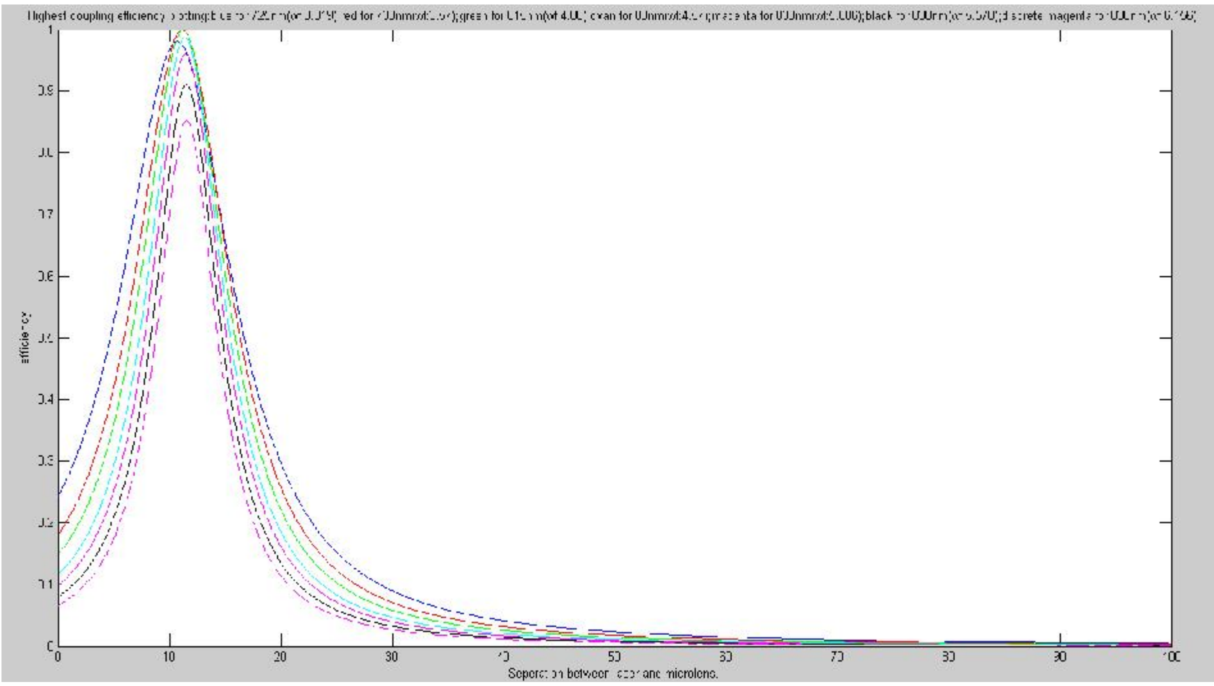

Hence, from the available result set its pretty obvious that with a fixed core diameter(4 micrometer in this case)and radius of aperture ,if we increase the spot size, then we can achieve maximum efficiency upto 100% in standard visual wavelength for human. Efficiency decreases with core diameter decrease and smaller spot sizes. From previous research works it has know that the wavelength 1.55 micro meters shows its maximum efficiency in terms of excitation efficiency. It also deserves mentioning in this connection that erbium doped fiber amplifier and Raman gain fiber amplifier work efficiently around the wavelength 1.5µm and as such the importance of 1.5µm is well understood in all optical technology.[18] Moreover, parabolic index fiber possesses the merit of large bandwidth and low sensitivity to micro as well as macro bending. Thus, such coupling device will emerge as a potential candidate in the field of optical technology.

IV.CONCLUSION

Using the ABCD matrix for refraction by a upside down tapered hyperbolic micro lens, drawn on single-mode parabolic index fiber, we formulate analytical expressions of the excitation efficiencies in absence of possible mismatches. As regards the execution of the formalism for evaluation of concerned coupling optics, MATLAB has been employed. Here, to investigate the coupling optics for the range of a standard human visual spectrum. It has been observed that the wavelength range which is,740 to 825 nano meter is more efficient as far as coupling efficiency is concerned.

specially from Illumination engineering point of view using visible light would be very much cost effective in this regard considering its bounty availability and since its pretty easy to generate in industrial environment. From the observation it has been concluded that, for industry standard it would always be advisable to choose suitably larger core and spot sizes so that without major loss maximum efficient level can be achieved. In this project, the efficiency is achieved 100% which should be a good enough level of efficiency to suit industrial needs.

APPPENDIX A

The laser beam input and output parameters (q_1,q_2) are connected by the region given below,

$q_2 = \frac{Aq_1+B}{Cq_1+D}$ (A.1)[9]

Where,

$\frac{1}{q_{1,2}} = \frac{1}{R_{1,2}} - \frac{j\lambda_0}{\pi w_{1,2}^2 n_{1,2}}$ (A.2)[6]

Here, R, n, w and λ_0 represent the radius of curvature of wave front, refractive index, spot size and the wavelength in free space respectively.[18]

The ray matrix M for the upside down tapered hyperbolic micro lens on the fiber tip is given by:

$M = \begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} \begin{pmatrix} 1 & u \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$ (A.3)

Here,

$A_1 = R_2(z) - \frac{(n_{c0}-1)}{n_{c0}\left(\frac{b^2}{a}\right)} R_1(z)$ (A.4)

$B_1 = \frac{1}{n_{c0}} R_1(z)$ (A.5)

$C_1 = n_{c0} \frac{dR_2(z)}{dz} - \frac{(n_{c0}-1)}{(b^2/a)} \frac{dR_1(z)}{dz}$ (A.6)

$D_1 = \frac{dR_1(z)}{dz}$ (A.7)

Here, b and a denote lengths of semi axes of the hyperbolic interface in the plane of the paper.

Further,

$R_1(z) = -\frac{L}{\eta}[G(z)]^{0.5} \sin[\eta \ln G(z)]$ (A.8)

$\frac{dR_1(z)}{dz} = \frac{1}{[G(z)]^{0.5}}\{\cos[\eta \ln G(z)] + \frac{1}{2\eta}\sin[\eta \ln G(z)]\}$ (A.9)

$R_2(z) = [G(z)]^{0.5}\{\cos[\eta \ln G(z)] - \frac{1}{2\eta}\sin[\eta \ln G(z)]\}$ (A.10)

$\frac{dR_2(z)}{dz} = \frac{A_0^2 L a_0^2}{d^2[G(z)]^{0.5}} \sin[\eta \ln G(z)]$ (A.11)

Where, z is the axial length along the tapered region, L is axial length from the end face of the fiber to the geometrical vertex of the tapered profile; d is the radius of the aperture.

Further, the used parameters G(z),η,A_0,z are given by,

$G(z) = 1 - \frac{z}{L}$ (A.12)

$\eta = \frac{A_0^2 L^2 a_0^2}{d^2} - \frac{1}{4}$ (A.13)

$A_0 = \frac{d\left(1-\frac{z}{L}\right)}{a_0^2}\left(1 - \frac{n_{cl}^2}{n_{co}^2}\right)^{0.5}$ (A.14)

$z = \frac{L(d-a_0)}{d}$ (A.15)

Further from equation (A.3),

$A = A_1, B = A_1 u + B_1, C = C_1, D = C_1 u + D_1$

The lens transformed spot sizes w2x,2y and radii of curvature R2x,2y are obtained by using equations (A.1),(A.2)[18]and the ABCD matrix given by (A.3) and those are given below,

$w_{2x,2y}^2 = \frac{A_2^2 w_{1x,1y}^2}{n(A_2 D - BC_2)} + \frac{\frac{\lambda_1^2}{\pi^2}\frac{B^2}{w_{1x,1y}^2}}{n(A_2 D - BC_2)}$ (A.16) [6]

$\frac{1}{R_{2x,2y}} = \frac{A_2 C_2 w_{1x,1y}^4 + (\lambda_1^4 BD)/(\pi^4 w_{1x,1y}^4)}{A_2^2 w_{1x,1y}^2 + (\lambda_1^2 BD)/(\pi^2 w_{1x,1y}^2)}$ (A.17)[6]

Where,$\lambda_1 = \frac{\lambda_0}{n_1}$, $A_2 = A + \frac{B}{R_1}$, $C_2 = C + \frac{D}{R_1}$ and $n = \frac{n_2}{n_1}$ [6]

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