Design and Evaluation of Immersed Wideband Non-polarizing Beam Splitter Using ZEMAX Program and Needle/ Tunneling Method

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Abstract—Herein a wideband non-polarizing cube beams splitters (NPBSs) for the telecommunication C-band. We engage analysis/simulation and design/optimization methods, using an optical design software ZEMAX-EE and Needle/Tunneling synthesis method to find optimal beam splitter parameters. Similar design parameters of minimum layers with ternary dielectric materials were introduced. The results show that ZEMAX software has the ability to design thin film non-polarizing beam splitters and in comparison to needle/tunneling method has reasonable result. Moreover, NPBSs are provided exhibiting ~ 50/50 beam ratio with reasonably tolerant deviations in angle of incidence.

Keywords— Non-polarizing beam splitter, Zemax-EE, Needle/Tunneling synthesis method, Optical design

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1 INTRODUCTION

Veam splitters and beam dividers are important elements in optical and photonic systems[1]. There are two main types of beam splitters: a) polarizing beam splitters (PBSs) that separate the polarization components of the input light and b) non-polarizing beam splitters (NPBSs) that divide the input light beam into two beams traveling in different directions, regardless of their polarization. NPBSs classified in two main configurations; plate and cube [1], [2]. In the plate type, the layers are deposited on a plane substrate while in the cubic form, the layers are deposited on the hypotenuse of two prisms and then these prisms are cemented together with an optical adhesive to produce a cube [1]. A common power division fraction is 50/50, but other ratios are also available. Fig. 1 shows a schematic view of a cubic NPBS.

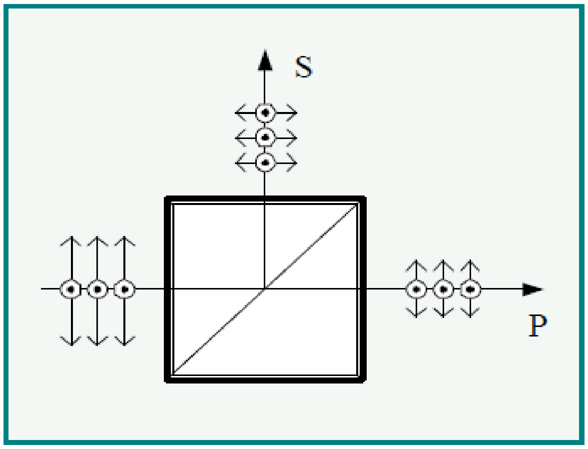

Fig. 1. Cubic non-polarizing beam splitter.

Design of cube beam splitter avoiding polarization problems is a much more difficult task than the design of polarizing components and there is no completely effective method. Only a few designs on all- dielectric, non-polarizing beam splitter have been published so far that describe different design concepts, good reviews on thin film NPBSs is in Refs. [2] to [14]. The relation between the transmittance and the degree of polarization in multilayer as a function of layer indices and the angle of incidence was described by Baumeister [8]. Costich [12] introduced a way to reduce polarization effects in multilayer, especially in metal-dielectric films with one air interface. Method of obtaining non-polarizing films inside a glass cube using quarter wave layer only was developed by Thelen [9]. Method for synthesizing of three layer equivalent periods with low polarization at oblique incidence was described by Knittl and Houserkova [10]. De Sterke et. al. [3] developed Thelen [9] procedure and achieves non-polarizing beam splitter when three materials of quarter wave thicknesses were used. A powerful design technique, needle optimization with basic idea of this technique was first proposed in 1982 by Tikhonravov [13], and then improved by DeBell et.al. [14] to achieve an optimal coating and filters. Al-Hamdani used ZEMAX software in different applications (microlens solar concentrator [16] and NPBs plate in C-band optical communication [16]. Our work represent the ability of adapting ZEMAX[17], and the application of needle like variation to design and optimized cube NPBSs of 50/50 ratio. In continuous of the previous studies [18]-[33] in the Energy and Renewable Energy Technology Center, we are focusing on the greater use of renewable energies in various applications suitable for Iraq climates.

2. THEORITCAL BACKGROUND

2.1. Characteristic matrix theory

From the Fresnel equation [5], [6] in air, the reflectance of a quarter wave stack at oblique incidence is:

$$R = \left(\frac{\eta_0 - Y}{\eta_0 + Y}\right)^2 \quad (1)$$

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$$Y= \left(\frac{\eta^2 1\ \eta^2 3\ \eta^2 5 \ldots \eta sub}{\eta^2 2\ \eta^2 4\ \eta^2 6 \ldots}\right) \qquad (2)$$

η is effective index of refraction, this is the refractive index of a medium, relative to the state of polarization of the radiation that crosses it. Thus, for the two linearly polarized components p (TM mode) and s (TE mode), we have [5]:

$$\eta_p = n/cos\theta, \qquad (3)$$

$$\eta_s = ncos\theta, \qquad (4)$$

"n" is the nominal refractive index of the layer; "θ " is the angle under the light passes through the layer. This is the angle of refraction, resulted from the Snell's Law. $n_0 \sin\theta_0 = n\sin\theta$.

The optical thickness of each layer is multiplied by cosθ and is named "the effective thickness". Using the Snell law, then, cosθ =[1- A2 / n2]1/2, where A= $n_0 \sin\theta_0$ (A is called numerical aperture). n_0 and θ_0 are the index of refractive of air and angle of incidence, respectively.

The characteristic matrix of an assembly of "q" layers, with $Y=\begin{bmatrix} C \\ B \end{bmatrix}$ is [5]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{r=1}^{q} \begin{bmatrix} \cos\delta_r & (i\sin\delta_r)/\eta_r \\ i\eta_r \sin\delta_r & \cos\delta_r \end{bmatrix} \right\} \begin{bmatrix} 1 \\ \eta_m \end{bmatrix} \qquad (7)$$

Optimum design can be accessed using a merit function defined as [11]:

$$MF = \left[\frac{1}{N} \sum_{j=1}^{N} \left[\frac{f(\lambda_i) - \hat{f_j}}{\Delta \hat{f_j}} \right]^2 \right]^{1/2} \qquad (8)$$

Where f is the actual spectral characteristic for transmittance or reflectance λ_j are wavelength points from a given wavelength grid with the total number of N points, $\hat{f_j}$ are target values, and $\Delta\hat{f_j}$ are specified tolerances at these points.

2.2. Needle/Tunneling method

Needle optimization is a powerful method for design multilayer coatings. It works by adding zero-thickness layers at precise locations in the design, and then allowing those new layers to grow (using local optimization)[13]. This procedure may be repeated until there are no locations where a new layer can grow. When this occurs, the final design is called "optimal". But the design still have not the desired performance, thus, the purpose of the tunneling method is to find another– better- local minimum. It does this by growing a layer which has the effect of tunneling to another valley of the merit function, as shown in Fig. 2.

A benefit of the needle/tunneling method is that the initial design can be very simple perhaps only 1 QWOT thick. The method will grow the design to meet the desired performance. Another benefit is that a sequence of designs is created, giving the designer a choice of designs to manufacture. Finally, this method excels and finding the thinnest design that meets a given performance specification; it just grows the design until the requirement is attained.

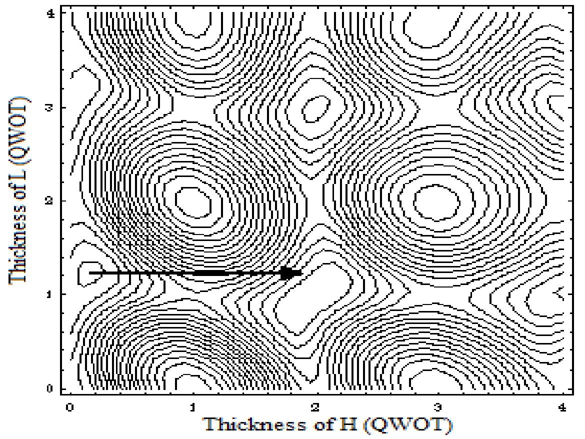


Fig. 2. Needle/tunneling method. The arrow indicates how this method tunneled from one valley to another.

3. RESULTS AND DISCUSSIONS

3.1. Effective indices

Ternary materials TiO_2 (2.43), Al_2O_3 (1.63) and SiO_2 (1.44) [18] were chosen as dielectric, non-dispersive high, medium, and low index of refraction, respectively immersed in BK-7 glass (1.52). The optical thicknesses of these layers are QWOT at 1.55μm, abbreviated as H, M, and L, respectively. Fig.(3) despite the relationship between η_s, η_p vs. nominal index of refract- ion "n" for an incidence of light of 45° from BK7. From figure it is clear that η_s curve has linear behavior of positive slope whereas η_p has minimum at n=1.52. The existence of a minimum value means that two indices from different sides of the minima have the same η_p.

This step helps us to find the two materials we need. We can observe that they should have the following approximate values: $n_L \approx 1.4$; $n_H \approx 1.7$.

3.2. Optimum design of non-polarizing cube beam splitter

To find optimal beam splitter parameters, we engage analysis/simulation and design/ optimization methods. This was done by using ZEMAX and Needle/tunneling synthesis methods. The initial design Choosing is not critical for the needle/ tunneling method, i.e. it is quite possible to starting design, for example, Glass|HML| glass. Because needle like variations having the ability to develop layers and change their positions during the optimal design procedure. Further, ZEMAX and Needle method both based on the characteristic matrix theory as thin film analysis. The aim is to design a 45° non-polarizing beam splitter cube, for a wave-length range as wide as possible, and centered at 1.550μm, with the following requirements performance:

$$| R_s - R_p | \le 2\%$$
$$40\% \le R_s \le 60\%$$
$$40\% \le R_p \le 60\%$$

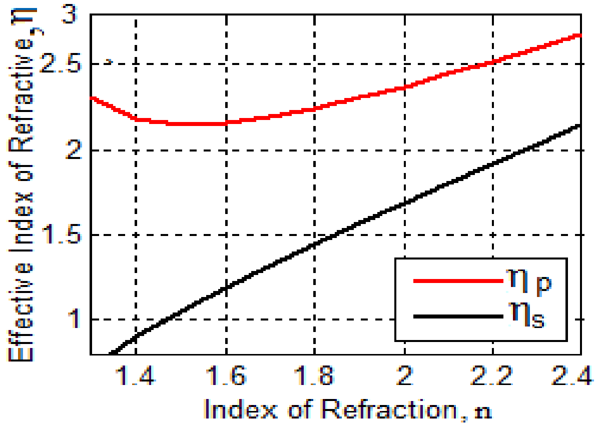


Fig. 3. Variation of the effective indices as a function for a nominal index n at 45˚ incidence angle and n0=1.52.

Three coating materials were used for NPBSs design, analysis and optimization. These materials are: L (1.44), M (1.63), and H (2.43).

A) Needle Optimization Synthesis:

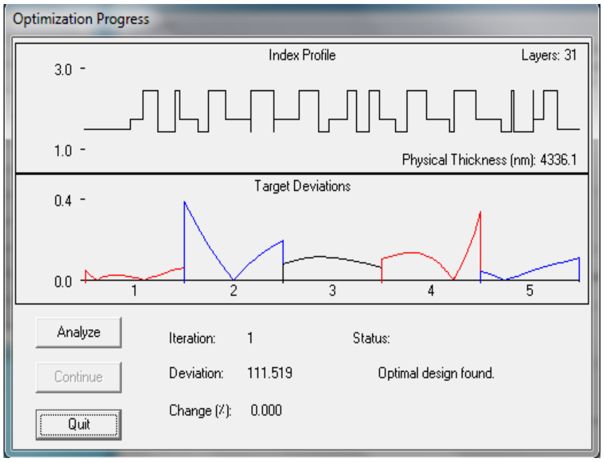
Starting with a thin, one-layer design, needle/tunneling method produced a sequence of designs of increasing complexity.

TABLE (1)

NPBSs target requirements

Target #	1	2	3	4	5
Kind	Intensity	Intensity	Intensity	Intensity	Intensity
Refl/Tran	Refl	Refl	Refl	Refl	Refl
Polarization	S	P	Ave	S	P
Wavelength (begin)	1.5	1.52	1.54	1.56	1.58
Wavelength (end)	1.52	1.54	1.56	1.58	1.6
Angle	45.0	45.0	45.0	45.0	45.0
Target (begin)	50.0	50.0	50.0	50.0	50.0
Target (end)	50.0	50.0	50.0	50.0	50.0
Tolerance	0.001	0.001	0.001	0.001	0.001
Environment	1	1	1	1	1

This extremely difficult design consists of 31- layers. The above requirements were translated into five continuous optimization targets, summarized in Table (1) and plots of optimization progress was shown in Fig.(4) using a maximum of 100 iterations and set the error tolerance to 1.0E-3. The maximum total thickness of 4336.1 nm, removing one very thin layer and re-optimizing without needle optimization, we obtain a 28-layer design, as shown in Fig.(5) and the final optimum design tabulated in Table(2).



Iteration: 1

Status: Optimal design found.

Deviation: 111.519

Change (%): 0.000

Fig. 4. NPBSs needle/tunneling optimization progress

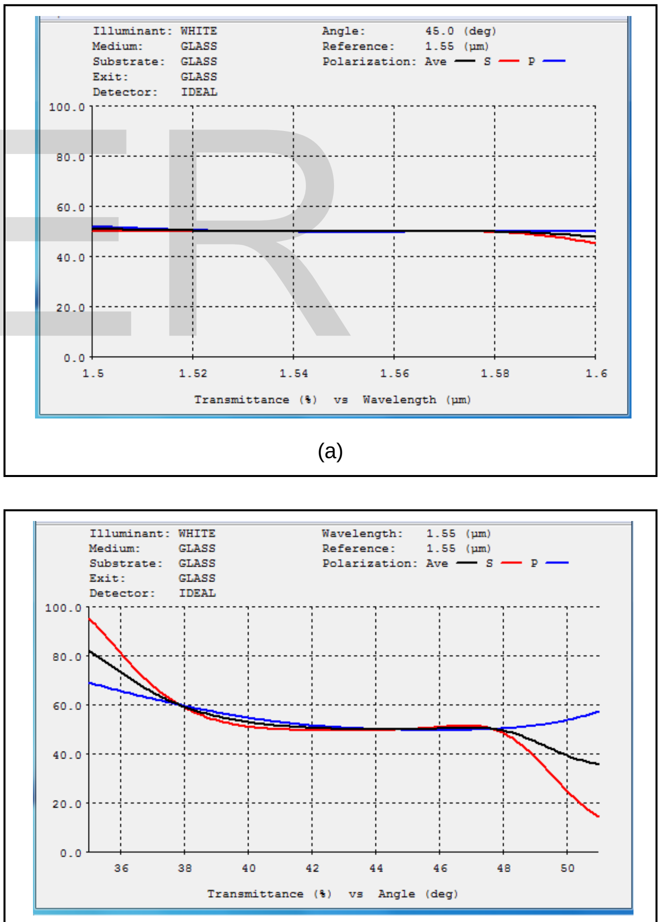


Fig. 5. Optimum neutral transmittance behavior of nonpolarizing cube beam splitter design using Needle/tunneling optimization vs. (a)Wavelength at angle incident 45°, (b) Incident angle at design wavelength 1.550μm.

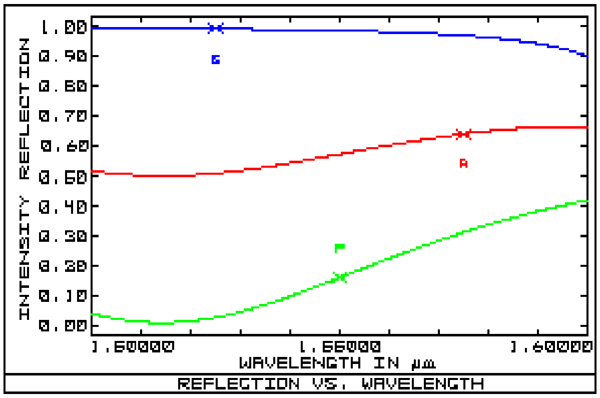
B) ZEMAX SOFTWARE

Depending on the designer experience, the, number and arrangement of the layers and building optimal algorithm in merit function were selected. Running “Hammer optimization” which included in ZEMAX-EE software; the optimum thickness of multilayer coating of the proposed design was constructed. The layer thickness was change from operand "CODA" that constrains the coating multiplier. An exhaustive searching for optimum solution included with ZEMAX enriched with a merit function of least squares form given in equation [8]. The spectral reflectance of this stack vs. wavelength and angle of incident for cube beam splitter are shown in Fig.6. This design was considered as a good "stating point" to optimization in the next step.

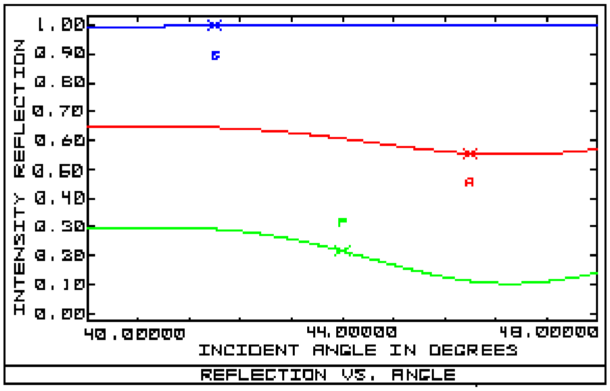
TABLE (2)

OPTIMUM DESIGN THICKNESS

NO. Layer	*Layer Symbol*	*Thickness (nm)*	*NO. Layer*	*Layer Symbol*	*Thickness (nm)*
1	M	133.73	15	L	166.14
2	H	116.92	16	H	80.21
3	L	221.35	17	M	179.57
4	H	33.66	18	L	154.19
5	M	198.74	19	H	152.58
6	L	130.91	20	M	246.79
7	H	138.15	21	L	55.79
8	M	274.04	22	H	172.12
9	H	174.43	23	M	267.80
10	M	274.71	24	L	132.04
11	H	152.53	25	H	13.76
12	L	134.40	26	L	254.04
13	M	192.99	27	M	107.22
14	H	72.73	28	H	104.56



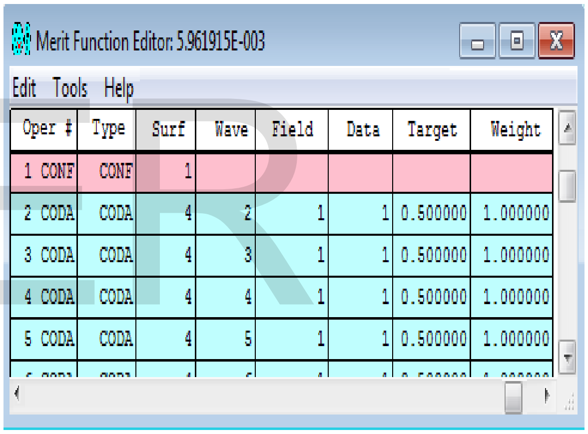
(a)



(b)

Fig. 6. Reflectance profile vs. (a) Wavelength for initial design plate beam splitter: air|(MHML)^{4}M| glass, at angle incident 45°, (b) Incident angle at design wavelength 1.550µm.

Fig.7. shows the simple part of the algorithm optimal design in merit function with ZEMAX-EE software.

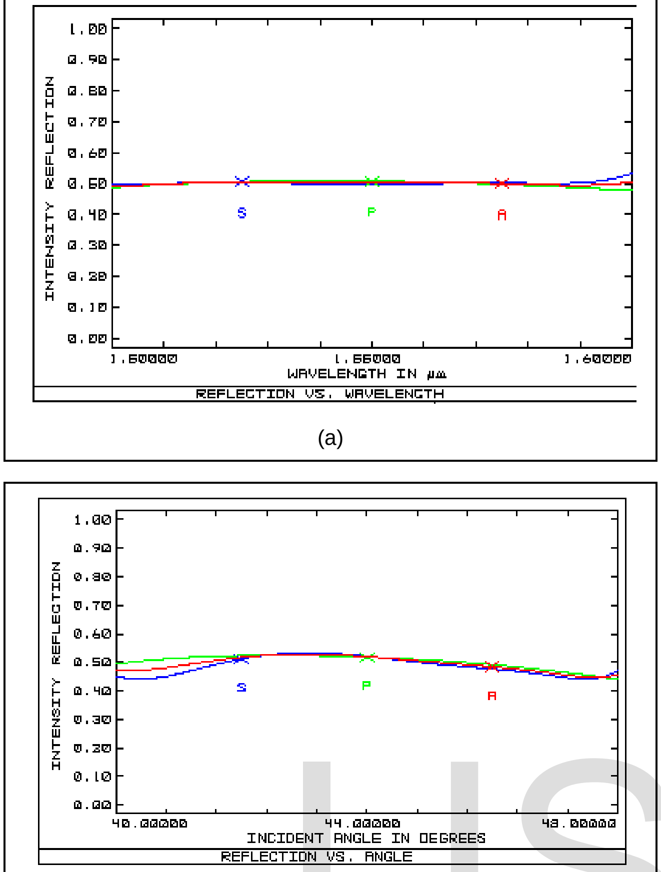


Oper #	Type	Surf	Wave	Field	Data	Target	Weight
1 CONF	CONF	1					
2 CODA	CODA	4	2	1	1	0.500000	1.000000
3 CODA	CODA	4	3	1	1	0.500000	1.000000
4 CODA	CODA	4	4	1	1	0.500000	1.000000
5 CODA	CODA	4	5	1	1	0.500000	1.000000

Fig. 7. Algorithm optimal design in merit functions of the ZEMAX.

The final design of neutral NPBSs is shown in Fig.8. The spectral reflectance shows that NPBs operating in C-band over a wide spectral wavelength (1.50-1.60µm) and angular view range (40-48°). The final optimum thicknesses are written in quarter-wave effective thickness at 45°:

$$\text{Glass}\left|\begin{array}{c}1.9975L\ 0.7599H\ 2.9063M\ 0.9060H\\ 1.3602M\ 1.1014H1.3234M\ 0.8274H\\ 0.8562L0.5418H\ 0.8871\ L\ 0.8861H\\ 1.0879M\ 0.2692L\ 1.0902H\ 1.2920M\\ 0.0590L\ 1.1344H\ 1.0917\ M\ 0.8974L\\ 1.9559H\ 1.6818L\ 0.5282M\ 0.8625H\end{array}\right|\text{Glass.}$$



(a)

(b)

Fig. 8. Optimum neutral reflectance behavior of non-polarizing cube beam splitter design using ZEMAX software vs. (a)Wavelength at angle incident 45°, (b) Incident angle at design wavelength 1.550µm.

5. CONCLUSIONS

In this paper, we present new NPBS of thin layer thickness aiming for 50/50 operating across the 1500–1600nm; spectral band (telecom C-band). To met these requirement, needle/ tunneling method and Zemax software were used .The optimum design consist of three dielectric materials arranged in 28-, 24- layers over a spectral width ~100nm and angular sensitivity ~10º. The analysis shows that ZEMAX has the ability get NPBSs of good performance with prior designer experience.

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