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ENERGY SAVING GLASS: MODELLING THE COATING DESIGN FROM MATHEMATICAL PERSPECTIVE

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Abstract

Buildings are recently equipped with special coated energy saving glass as window. The function of this glass is to be the outer shell that protects us from the exposure of dangerous Ultra-violet rays, direct sunlight and heat. The glass is also able to maintain the internal temperature at a suitable condition in the building. The invention of this energy saving with extensive technology of low-emissivity glass is very significant in our daily lives, which can help in reducing the electricity usage. However, the glass attenuates communication signals such as global positioning system, mobile phone and wireless broadband; due to the fabricated coating layer on the window. Therefore, this paper aims to propose a new mathematical model of optimum coating design for the energy saving glass. It uses Harmony search to obtain the optimum result. The model starts by manipulating the plate design into desired grid and fill in the grid with binary number based on the mathematical model. The optimum binary result is then converted into coating shape design for energy saving glass in the Computer Simulation Technology Studio. The performance of transmission coefficient and return loss is used to evaluate the resulted shape design structure in which, the resulted efficiency is 99.88%.

Keywords: Communication signal, Energy saving glass, Harmony search, Mathematical model, Optimization.

1. Introduction

Energy saving glass is one of the modern invention, which it has significant contribution in the modern architecture [1-3]. The heating and the cooling cost can be reduced by 10-33% if the building is using the window with energy saving glass [2, 4]. Jasmi et al. [5] mentioned that it is now a common material in the industry of manufacturing as the green technology demand is increasing widely. However, it still has some weaknesses, which requires attention for continuous improvement. One of the weaknesses is that the glass attenuates communication signals and this is due to the metallic-oxide coat, which is fabricated on the glass [5-8]. Hence, useful signals that are required for communications are wasted because of the coating. Nevertheless, the presence of the coating is one of the foremost criteria of energy saving glass in which, it function as a thermal isolator. This is in line with green-technology that intends to reduce electricity usage. Sohail et al. [9] proposed that it can be seen that due to the presence of the coating, the radio frequency signals are distracted, which in turn result in low transmission. Hence, the work of developing a new optimum shape design is needed for the energy saving coating structure. According to Tideman et al. [10], it must be noted that design process is a significant process to produce efficient and quality product.

Since the design of the coating requires attention for better energy saving glass, therefore, the development of optimum complex shape design for energy glass coating structure, which may differ from previous regular shapes, will be presented in this paper. The mathematical model for optimum shape design of energy saving glass coating structure will be presented in second section. The model will be applied by using harmony search in order to obtain the optimum shape design. The result will be presented and discuss in third section. Finally, the last section concludes the paper.

2. Methodology

In our daily life, there are various natural sciences, engineering discipline [5, 11, 12] as well as social sciences [13, 14] that require mathematical model to explain, represent and investigate the system. In this paper, instead of following the common approach of modifying the regular shape, a new complex shape design for the coating of the energy saving glass is created based on the developed mathematical model. This approach is totally different from the existing work. The new complex shape design is the optimized shape design that will result in reducing the amount of lost transmission signals. In other words, certain frequencies are allowed to pass through the energy saving glass.

The procedure starts by firstly manipulates the empty plate in order to create a new complex shape design. Figure 1 illustrates how this procedure works. From an empty space on the plate, multiple smaller square shapes are formed by drawing the grid lines. The size of the multiple smaller square shapes or the grids depends on the number of grids generated. For example, higher number of grids will results in smaller size of grid given that the same size of plate is applied. The empty space is gridded because it would serves as a guidance to determine, which area or space will be coated or will be left uncoated. It must be noted that the uncoated space allow the signal to pass through, and it gives a huge impact on the return loss and transmission coefficient. The uncoated space should be close to each other in order to be more effective. In this work, the binary values of '0' and '1' will represent the uncoated and coated space respectively on the energy saving glass.

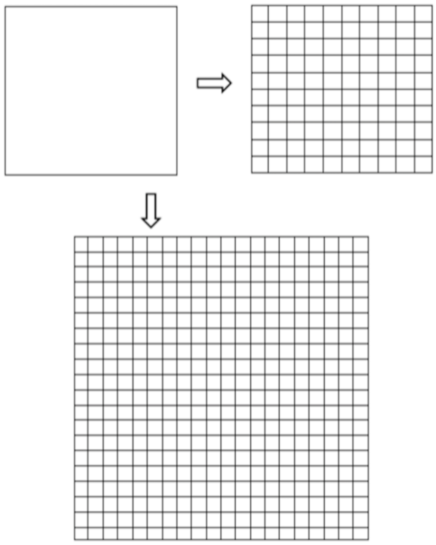

Fig. 1. Manipulation of empty plate into grid.

Each element of the grid can be tag in the form of its row and column number as illustrated in Fig. 2. Hence, the row and column number are represented by index *i* and *j* respectively where $i = 1, 2, 3, .., N$ and $j = 1, 2, 3, .. , N$. For example, the element from the first row and third column can be tag as x_{13}. Next, each element must be categorized as either coated or uncoated. Hence, for easy calculation, coated element is assigned as bit '1' while uncoated element is assigned as bit '0' on the grid. In this paper, only 40% of the whole area of the plate is coated as specification for shape design structure while the rest are left uncoated. The initial experiments were done for coated area of 60%, 50% and 40%. The best result is shown in the paper, which are using 40% coated and 60% uncoated region for the wireless signal. The impact of increasing coated area will result in high reflection or attenuation for the communication signal due to wide surface is being covered. On the other hand, decreasing the coated area will allow more and wide range of communication signal to pass through, but this may affected the energy saving glass main function in reducing energy consumption.

Once each element has been assigned its value of 1 or 0, the model works by grouping together each bit 0 encountered successively along each row *i*. This group is represented as $t_{i,k}$ in which, *i* denotes the row number while *k* denotes the group number appears in the respective row *i*. Following the work from Johar et al. [15], each group is assigned with fitness point as presented in Table 1.

For each row *i*, the weightage W_i is obtained by summing all the fitness points from all the $t_{i,k}$. This procedure of assigning the fitness point as well as summing the value of fitness point as row weightage is done to every row. The example to assign the fitness value as well as to calculate the weightage for row 2 is illustrated as in Fig. 3.

Table 1. Good fitness point.

Number of zeros (bits)	Points
0	1
00	2
000	3
0000	2
00000+	1

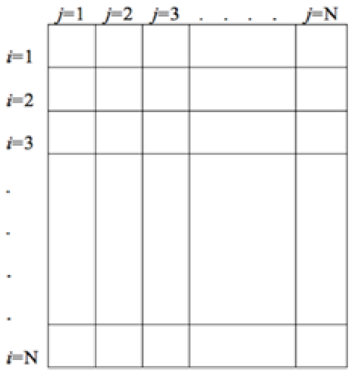

Fig. 2. Dimension grid representing the whole coating layer design.

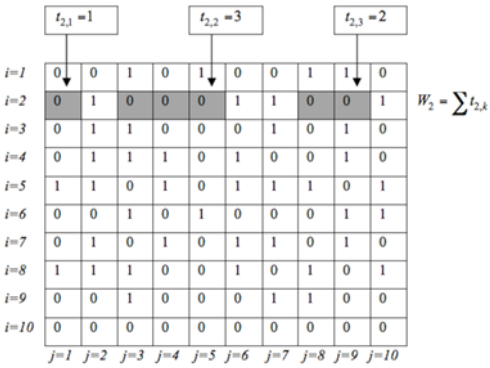

Fig. 3. Weightage calculation.

Based on Fig. 3, there are a total of three groups and the fitness values are assigned as follows:

Group 1: $t_{2,1}=1$

Group 2: $t_{2,2}=3$

Group 3: $t_{2,3}=2$

Therefore, row 2 has the following weightage as denoted in Eq. (1):

$$W_2=\sum t_{2,k} \tag{1}$$

$W_2 = t_{2,1} + t_{2,2} + t_{2,3} = 1 + 3 + 2 = 6$

Once every row has been identified with its weightage, then the summation of all the weightage from every row ΣW_i is done. It must be noted here that this work choose ΣW_i as a criteria in order to determine the resulted shape design is optimum or not. Hence, the mathematical model for the shape design of coating layer structure is formulated as follows:

$$\text{Min } \sum_{i=1}^{N} W_i \quad (2)$$

Subject to:

$$x_{ij} = \begin{cases} 1 & if\ x_{ij}\ is\ coated \\ 0 & if\ x_{ij}\ is\ uncoated \end{cases} \quad (3)$$

$$\frac{\sum x_{ij}}{N^2} = 0.4 \quad (4)$$

$$W_i = \sum_{K=1}^{K} t_{i,k} \quad ;\forall i \quad (5)$$

The objective function, which is the minimum value of total row weightage, reflects optimum shape design structure as denoted in Eq. (2). The constraint that specifies the element of the grid as coated or uncoated is denoted in Eq. (3). Equation (4) is the constraint that specifies that only 40% of shape design is coated. Finally, the weightage value assigned to each row is denoted in Eq. (5).

3. Results and Discussion

The mathematical model applies harmony search algorithm [16-21] in order to obtain optimum shape design structure. The process starts by initializing the random generated bits '0' and '1' at the $N \times N$ dimension grid. It must be noted that improvisation process is done iteratively until it meet the stopping criteria. Next, the optimum binary result (in the dimensional grid obtained from applying harmony search) is converted into coating shape design for energy saving glass in the CST Studio (Microwave).

In order to run the simulation of the resulted coating shape design in the CST Studio, unit testing are initially defined in order to meet the energy saving glass properties such as the dimension of the glass (in millimeter, mm), temperature (in Kelvin, K), frequency unit (in GHz) and time measurement (in second). Next, the range of frequencies to be tested on the shape design is set ranging from 0 Hz until 5 GHz for this research. These range of frequencies covers broadcasting telecommunications, mobile telecommunication as well as wireless fidelity (Wi-Fi) and wireless broadband (WiMax, LTE). Then, glass boundary condition is set up in order to meet the real situation of energy saving glass being applied on any building as a shield. This glass is influenced by the presence of electricity, magnetic field and open vacuum space in the glass. These three aspects have an effect on the transmission signals passing through the glass. The material of coating for the simulation is metallic-oxide.

There are two important indicators for performance evaluation, which are the return loss (S1,1) and the transmission coefficient (S2,1) in order to evaluate the resulted shape design structure. Transmission coefficient (S2,1) is a term applied in telecommunications generally, which is the ratio of the amplitude of the complex transmitted wave to that incident wave at a discontinuity in a transmission line. It is also reflected as the quality of a telecommunication line. On the other hand, return loss (S1,1) is the loss in power of the signal reflected by a discontinuity in a transmission line. These two aspects are visualized in a graph.

Table 2 shows the result for the 400 bits or 20 by 20 grid dimensions. The grid size selected for analysis is 400 mm by 400 mm. As can be seen in the table, there are 10 experiments and each experiment is repeated for 10 times. Each experiment has different number of iteration in which, it starts from 100^{th} until 1000^{th}. It can be seen that for the return loss (S1,1), the value obtained are almost over -30 dB, which means that the complex designs are appropriate and functional for wireless communication. It must be noted that the minimum requirement of return loss, which is considered as the bottom line for signal reflection, is at -10 dB. In this experiment, the result for return loss range from -29 dB up to -43 dB. The transmission coefficient represents the efficiency that is represented by a value as nearest as possible to ‘0’. It can be seen that the experiments indicate a comparable result with regards to the transmission coefficient value that range from -0.007 dB to -0.079 dB.

Each of the design resulted from every experiment is illustrated in Fig. 4(a)-(j) respectively. From Table 2, the optimum coating design for energy saving glass is obtained through second experiment (200 iteration) with the most minimum value of objective function (168), where the return loss (S1,1) is -43.38 dB and the transmission coefficient (S2,1) is -0.005 dB. The optimum coated designed resulted from second experiment is shown in Fig. 4(b). The associated graph performance analysis (on return lost and transmission coefficient) obtained from CST Studio for selected optimum design is illustrated in Figs. 5(a) and (b).

The efficiency of the above optimum shape design is evaluated as follows:

$$S2{,}1 = 10 \log E \qquad (6)$$

$$-0.005 = 10 \log E$$

$$E = 0.9988 \times 100$$

$$E = 99.88\%$$

Table 2. Result of performance for 400 bits dimension.

Experiment	1	2	3	4	5	6	7	8	9	10
Iteration	100	200	300	400	500	600	700	800	900	1000
Value of objective function	178	168	180	180	184	174	174	188	174	188
Return loss (S1,1) dB *negative value	32.01	43.38	35.35	40.33	42.12	31.11	35.48	29.9	31.19	40.12
Transmission coefficient (S2,1) dB *negative value	0.007	0.0047	0.0067	0.049	0.052	0.083	0.024	0.014	0.009	0.012
Frequency (GHz)	2.305	1.34	2.8	1.368	0.885	4.734	2.304	1.93	3.06	2.082

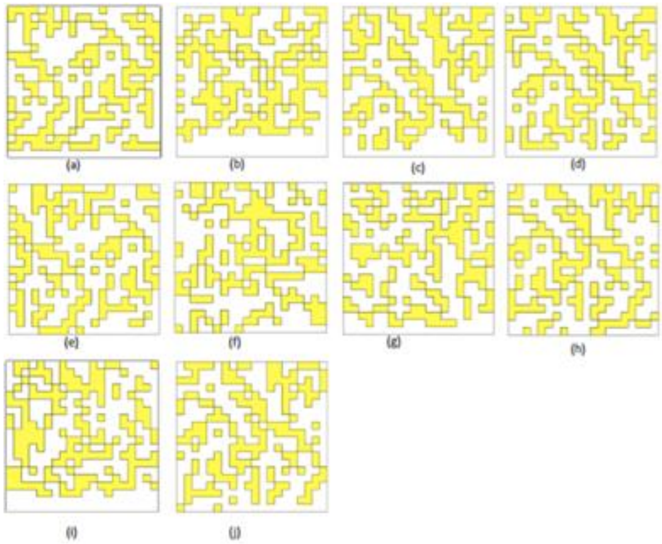

Fig. 4. Coated glass design resulted from experiment 1 until 10:
(a) Experiment 1, (b) Experiment 2, (c) Experiment 3, (d) Experiment 4,
(e) Experiment 5, (f) Experiment 6, (g) Experiment 7, (h) Experiment 8,
(i) Experiment 9, and (j) Experiment 10.

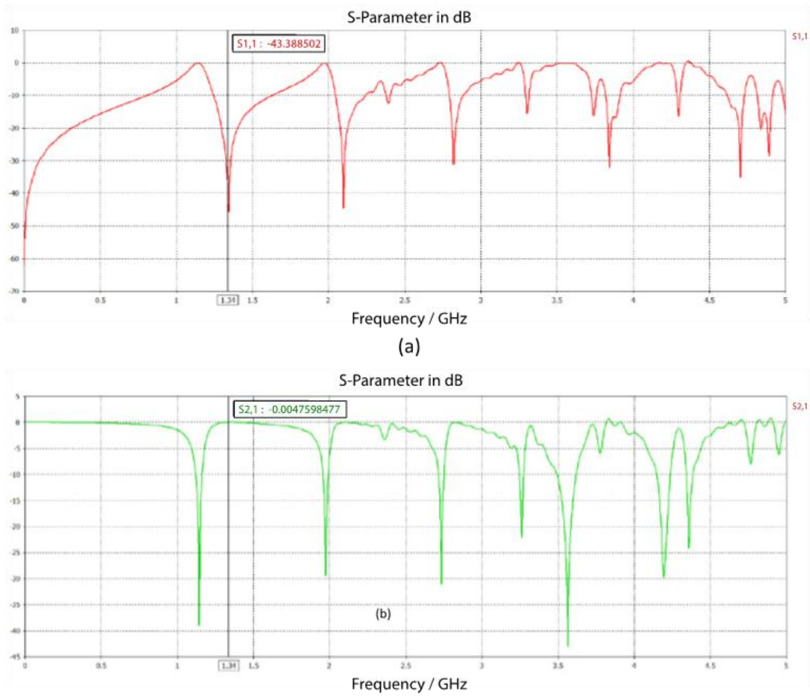

Fig. 5. Associated graph performance
analysis for optimum design (Experiment 2):
(a) Performance analysis for the design - return loss (S1,1) and
(b) Performance analysis for design - transmission coefficient (S2,1).

4. Conclusion

This paper illustrates the development of the mathematical model for energy saving glass coating design. Developing mathematical model for energy saving glass can be beneficial for having optimum energy saving glass coating design. This model applies Harmony search for solving the optimization model. The result from the experiments showed that return loss, transmission coefficient and efficiency are measured; the outcome of this research has contributed to efficiency of 99.88%. As a conclusion, the complex shape design resulted from the model would be able to cater the problems of the attenuation on transmission signal of wireless communication. More ever, the resulted shape design can be applied for various applications such as mobile phone (GSM, UMTS) and wireless network (Wi-Fi), which fall under 2.4 GHz frequency.

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Nomenclatures

N	Total number of row or column
S1,1	Return loss
S2,1	Transmission coefficient
$t_{i,k}$	Good fitness point of group *k* at row *i*
W_i	Weightage of row *i*
x_{ij}	Grid element of row *i* and column *j*

Abbreviation

CST	Computer Simulation Technology

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