



Transmission in combination of structures

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ABSTRACT

Purpose: The paper investigated the effect of the combination of two structures on the transmission of electromagnetic waves as a multilayer filter. Examined how the combination of two structures affect the properties of the filter. As a component materials of structures used both right-handed material (RHM) and left-handed (LHM).

Design/methodology/approach: Analysis was performed using a matrix method for calculating the superlattice transmission. The influence of combination of two types of multilayer systems: periodic (binary superlattice) and aperiodic (Severin's and Thue-Morse's superlattices).

Findings: Studies have shown the structure of the transmission band of the structures, which is dependent on the polarization of the incident wave. Combination of various structures are not commutative, and therefore their transmission maps are not equal.

Research limitations/implications: The structures analyzed in the work consisted of a lossless material, isotropic and non-dispersive. An important analysis would be lossy dispersive materials. You should also examine the impact would have a separating layer structure and the influence of defects on transmission properties of superlattices.

Practical implications: The test structures may be used as filters of electromagnetic radiation. Placing the filter characteristics of the two structures allows pre-filtering an electromagnetic wave, in order to obtain a structure suitable for applications.

Originality/value: The paper shows how combination of two periodic and aperiodic structures affect the propagation of electromagnetic waves in a multi-layered system. The analysis was based on the determination of unpolarized transmission maps for complex structures.

Keywords: Transmission; Multilayers; Superlattices; Aperiodic; LHM; RHM

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MATERIALS

1. Introduction

Multilayer systems, also called superlattices, enjoying the unflagging interest [1-5] due to their specific properties. A characteristic feature is the phenomenon of the photonic band gap. As filtration systems multilayer structures are usually created

with dielectric materials, but are expected properties of such structures already created with modern left-handed materials, known as metamaterials. In his theoretical work Veselago predicted the existence of metamaterials [6]. Experimental confirmation of his theory came after 32 years [7]. This fact has caused interest in left-handed materials more research centers [8-17].

Technology of obtaining different types of photonic materials are well developed [18-39].

In this work are described multilayer systems whose production technology allows you to create structures of selected layer thicknesses and types of materials [40-44]. Simulation allows design superlattice structures with transmission properties appropriate to the application.

Matrix method [2,15] for calculating the transmission of the multi-layer determines the propagation of electromagnetic wave in dielectric superlattices by the equation

$$\begin{bmatrix} E_{in}^{(+)} & E_{in}^{(-)} \end{bmatrix}^T = \Psi \begin{bmatrix} E_{out}^{(+)} & E_{out}^{(-)} \end{bmatrix}^T \quad (1)$$

where $E_{in}^{(+)}$ is the amplitude of the electric field intensity of an electromagnetic wave (EMW) incident into the system; $E_{in}^{(-)}$ and $E_{out}^{(+)}$ define respectively the amplitude of the reflected and passing intensities for EMW; $E_{out}^{(-)}$ is always zero.

Matrix Ψ is called the characteristic matrix of the system and is defined as

$$\Psi = A_{in,1} \cdot \left[\prod_{j=1}^J \begin{bmatrix} e^{id_j n_j \frac{2\pi}{\lambda} \cos \Theta_j} & 0 \\ 0 & e^{-id_j n_j \frac{2\pi}{\lambda} \cos \Theta_j} \end{bmatrix} \cdot A_{j,j+1} \right] \quad (2)$$

where Θ_j is the angle of incidence of the electromagnetic wave to layer j determined from Snell's law, λ - wavelength of the incident electromagnetic wave, d_j - thickness of the layer j , n_j - refractive index of the layer j , and $A_{j,i}$ is a matrix that describes the behavior of the electromagnetic wave on the verge of materials. Matrix $A_{j,i}$ depends on the polarization, and for the polarization P is defined as

$$A_{j,i}^P = \frac{n_j \cos \Theta_j + n_i \cos \Theta_i}{2n_j \cos \Theta_j} \quad (3)$$

$$\begin{bmatrix} 1 & \frac{n_j \cos \Theta_j - n_i \cos \Theta_i}{n_j \cos \Theta_j + n_i \cos \Theta_i} \\ \frac{n_j \cos \Theta_j - n_i \cos \Theta_i}{n_j \cos \Theta_j + n_i \cos \Theta_i} & 1 \end{bmatrix} \quad (4)$$

whereas for the polarization type S matrix $A_{j,i}^S$ is defined as:

$$A_{j,i}^S = \frac{n_j \cos \Theta_i + n_i \cos \Theta_j}{2n_j \cos \Theta_j} \quad (5)$$

$$\begin{bmatrix} 1 & \frac{n_j \cos \Theta_i - n_i \cos \Theta_j}{n_j \cos \Theta_i + n_i \cos \Theta_j} \\ \frac{n_j \cos \Theta_i - n_i \cos \Theta_j}{n_j \cos \Theta_i + n_i \cos \Theta_j} & 1 \end{bmatrix} \quad (6)$$

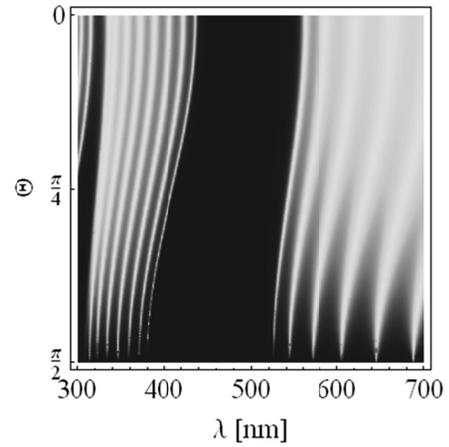


Fig. 1. Polarized transmission map of the binary superlattice for $L = 8$ and polarization type S

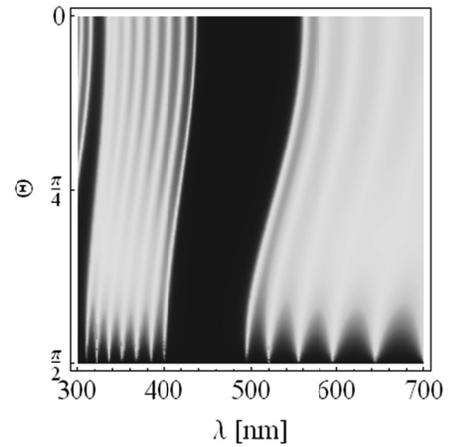


Fig. 2. Polarized transmission map of the binary superlattice for $L = 8$ and polarization type P

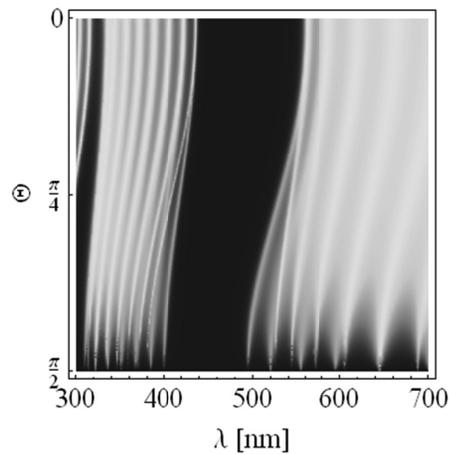


Fig. 3. Unpolarized transmission map of the binary superlattice for $L = 8$

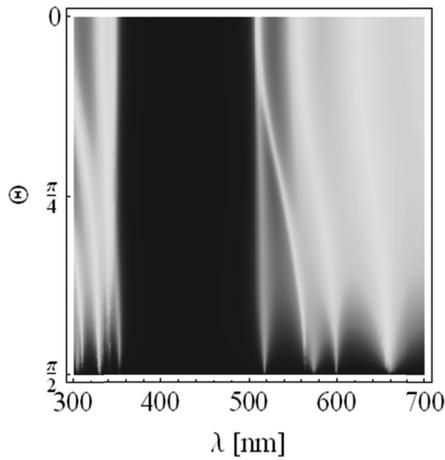


Fig. 4. Unpolarized transmission map of the binary superlattice for $L = 8$ and $n_B = -3.4$

After defining factor b associated with the type of surroundings material and angle of incidence of the electromagnetic wave as

$$b = \frac{n_{out} \cos \Theta_{out}}{n_{in} \cos \Theta_{in}} \quad (7)$$

can be determined transmission of an electromagnetic wave propagating in a multilayer structure directly from the first element of the characteristic matrix Ψ_{11} as:

$$T = b \cdot Abs(\Psi_{11}^{-1})^2 \quad (8)$$

for a given polarization. By using the Malus law transmission can be determined for any angle of torsion φ oscillation plane of the electric field intensity vector E

$$T(\varphi) = T^P \cos^2 \varphi + T^S \sin^2 \varphi \quad (9)$$

2. Research

Transmission maps are graphs showing the transmission T of the structure, where the white color indicated 100% transmission whereas black is 0%. The polarized transmission maps show transmission of the electromagnetic wave with the polarization P or S. In contrast, unpolarized transmission maps show the percentage of unpolarized incident wave propagates in the system through a multi-layer medium. Sample polarized and unpolarized transmission maps of binary superlattices show Figs. 1-4. A multilayer transmission is related to the wavelength of the incident electromagnetic wave $\lambda[nm]$ selected on the horizontal axis and the angle of incidence of the electromagnetic wave and the normal to the surface of the quasi one-dimensional non-dispersive lossless multilayer system.

The materials were used in the simulations NaCl as material A with a refractive index $n_A = 1.544$ [2] and GaAs as a B material whose refractive index is $n_B = 3.4$ [2]. In the part of the simulation is used metamaterial as the GaAs equivalent with a refractive index $n_B = -3.4$. The thicknesses of the layers in the structures were respectively $d_A = d_B = 100 [nm]$.

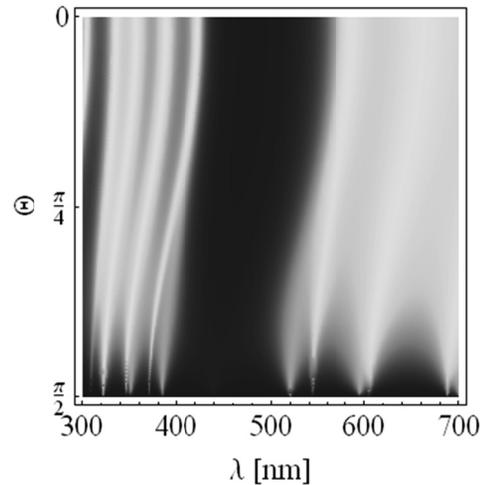


Fig. 5. Unpolarized transmission map of the binary superlattice for $L = 4$

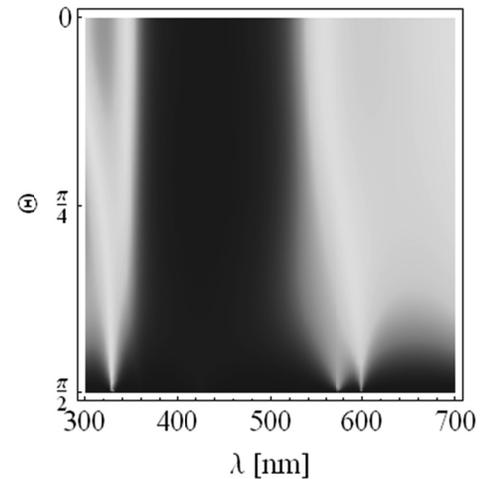


Fig. 6. Unpolarized transmission map of the binary superlattice for $L = 4$ and $n_B = -3.4$

2.1. Binary superlattice

The structure of the binary superlattices X_L^B is composed of L repetitions cluster AB. The number of L called a generation number. AB cluster consists of the A material having a thickness d_A and a refractive index n_A and a material B having a thickness d_B and a refractive index n_B . Equation (8) shows the steps to create a binary superlattices for the first three generations of L .

$$\begin{aligned}
 X_1^B &= AB \\
 X_2^B &= ABAB \\
 X_3^B &= ABABAB
 \end{aligned}
 \tag{10}$$

The structure arrangement of layers for binary superlattices of different generations is shown in Table 1. Figs. 5 and 6 show the unpolarized transmission maps for binary superlattice with generation number equals $L = 3$ for B material right and left-handed.

Table 1. Structure of arrangement of the layers for different generations L of the binary superlattices

L	X_L^B
1	AB
2	ABAB
3	ABABAB
4	ABABABAB
5	ABABABABAB
6	ABABABABABAB
7	ABABABABABABAB

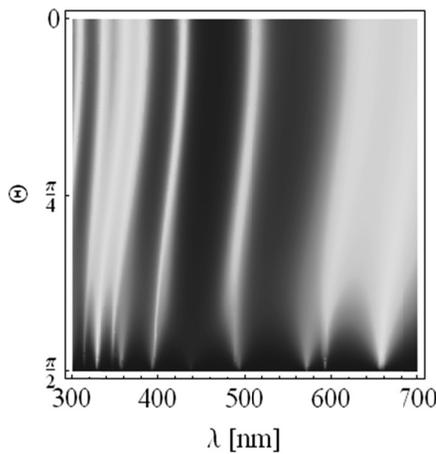


Fig. 7. Unpolarized transmission map of the Severin superlattice for $L = 3$

2.2. Severin superlattice

In order to obtain the aperiodic Severin structure [45] X_L^S use the recursive rule of substitution

$$\begin{cases}
 A \rightarrow BB \\
 B \rightarrow AB
 \end{cases}
 \tag{11}$$

at the initial condition $X_0^S = B$ gives the next three generations of superlattice Severin described by the formula (10), Table 2 lists the first seven generations of the superlattice.

In Figs. 7 and 8 show unpolarized transmission maps for Severin superlattices with $L = 3$.

$$\begin{aligned}
 X_0^S &= B \\
 X_1^S &= AB \\
 X_2^S &= BBAB
 \end{aligned}
 \tag{12}$$

Table 2. Structure of arrangement of the layers for different generations L of the Severin superlattices

L	X_L^S
1	AB
2	BBAB
3	ABABBBAB
4	BBABBBABABBBAB
5	ABABBBABABABBBABBBABBBABABABBBAB
6	BBABBBABABABBBABBBABBBABABABBBAB ABABBBABABABBBABBBABBBABABABBBAB
7	ABABBBABABABBBABBBABBBABABABBBAB ABABBBABABABBBABBBABBBABABABBBAB BBABBBABABABBBABBBABBBABABABBBAB ABABBBABABABBBABBBABBBABABABBBAB

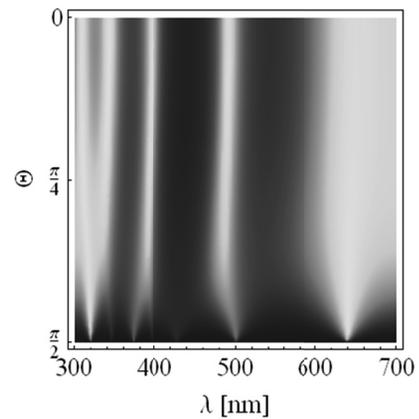


Fig. 8. Unpolarized transmission map of the Severin superlattice for $L = 3$ and $n_B = -3.4$

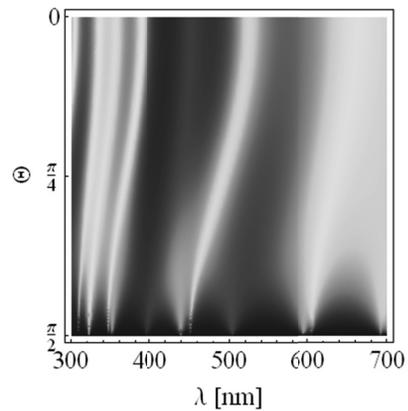


Fig. 9. Unpolarized transmission map of the Thue-Morse superlattice for $L = 3$

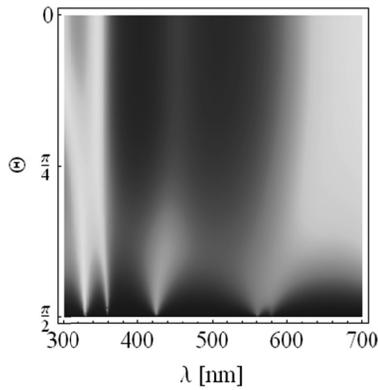


Fig. 10. Unpolarized transmission map of the Thue-Morse superlattice for $L = 3$ and $n_B = -3.4$

2.3. Thue-morse superlattice

Obtaining the Thue-Morse superlattices [46-52] X_L^{TM} requires the use of a recursive dependence described in formula (13).

$$\begin{cases} A \rightarrow AB \\ B \rightarrow BA \end{cases} \quad (13)$$

taking as initial condition $X_0^{TM} = A$ you can get another three generations of Thue-Morse superlattices (12).

Table 3 shows the structure of the Thue-Morse superlattices for generations of L number from 1 to 7.

Fig. 9 shows an unpolarized transmission maps to the third generations of Thue-Morse superlattice in the case where A and B are dielectric materials. In contrast, in Fig. 10 the material B is the left-handed material, which means that the refractive index of the material is negative.

$$\begin{aligned} X_0^{TM} &= A \\ X_1^{TM} &= AB \\ X_2^{TM} &= ABBA \end{aligned} \quad (14)$$

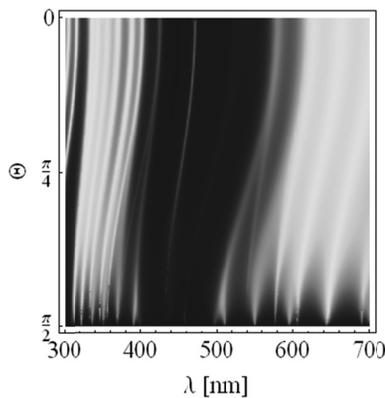


Fig. 11. Combination of B-TM for $L=3$ and $n_B = 3.4$

Table 3. Structure of arrangement of the layers for different generations L of the Thue-Morse superlattices

L	X_L^{TM}
1	AB
2	ABBA
3	ABBABAAB
4	ABBABAABBAABABBA
5	ABBABAABBAABABBABAABABBAABBABAAB
6	ABBABAABBAABABBABAABABBAABBABAAB BAABABBAABBABAABABBABAABBAABABBA
7	ABBABAABBAABABBABAABABBAABBABAAB BAABABBAABBABAABABBABAABBAABABBA BAABABBAABBABAABABBABAABBAABABBA ABBABAABBAABABBABAABABBAABBABAAB

2.4. Combination of b-tm and tm-b

Combination of B-TM is to build a binary structure, which was imposed the Thue-Morse structure. This can be described as

$$X_L^{B-TM} = X_{L+1}^B + X_L^{TM} \quad (15)$$

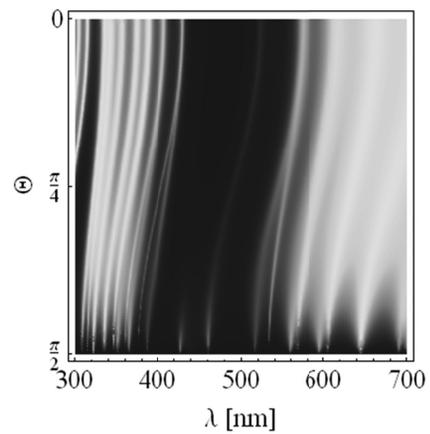


Fig. 12. Combination of TM-B for $L=3$ and $n_B = 3.4$

With combination of (13) for $L = 3$ we obtain the structure

$$X_3^{B-TM} = ABABABABBABAAB \quad (16)$$

TM-B on the other hand can be described as

$$X_L^{TM-B} = X_L^{TM} + X_{L+1}^B \quad (17)$$

which for $L = 3$ leads to the structure

$$X_3^{TM-B} = ABBABAABABABABAB \quad (18)$$

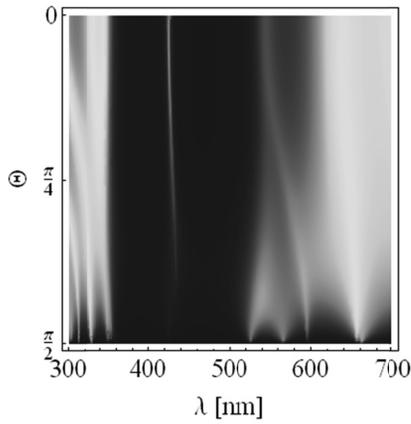


Fig. 13. Combination of B-TM for L=3 and $n_B = -3.4$

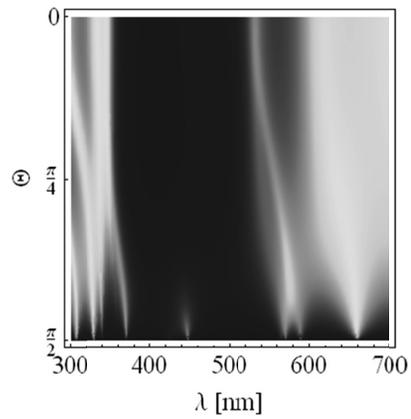


Fig. 14. Combination of TM-B for L=3 and $n_B = -3.4$

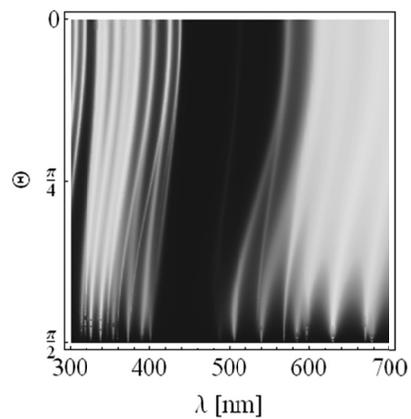


Fig. 15. Combination of B-S for L=3 and $n_B = 3.4$

In Figs. 11-14 are shown unpolarized transmission maps for combinations of superlattices B-TM and TM-B for L = 3. Figs. 11 and 12 show maps where $n_B = 3.4$. In contrast, in Figs. 13 and 14, the material B belong to metamaterials, and its refractive index is $n_B = -3.4$.

2.5. Combination of b-s and s-b

Just like in combination B-TM combination B-S is to impose on the binary structure the Severin structure. This describes the dependence (17).

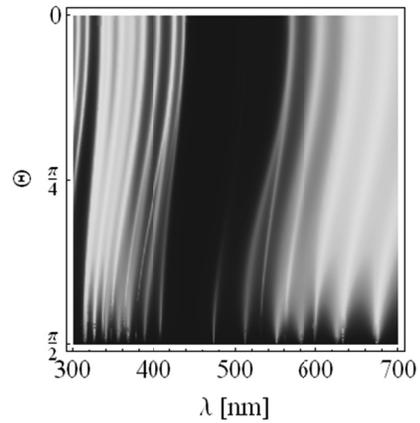


Fig. 16. Combination of S-B for L=3 and $n_B = 3.4$

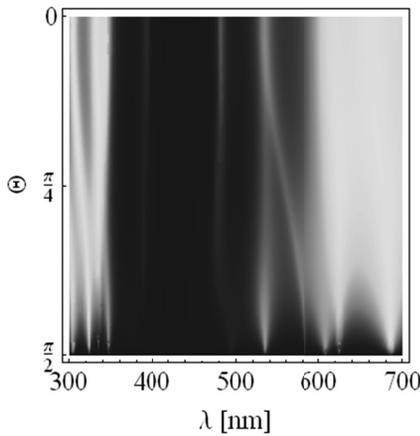


Fig. 17. Combination of B-S for L=3 and $n_B = -3.4$

$$X_L^{B-S} = X_{L+1}^B + X_L^S \tag{19}$$

It allows for L = 3 receive

$$X_3^{B-S} = ABABABABABBBBAB \tag{20}$$

In the case of a combination of TM-B has the formula

$$X_L^{S-B} = X_L^S + X_{L+1}^B \tag{21}$$

Because of that for L = 3 we obtain

$$X_3^{S-B} = ABABBBABABABABAB. \tag{23}$$

It should be noted that the combinations X_L^{B-S} and X_L^{S-B} are cases of structure defects of X_B^S . Figs. 15-18 show the unpolarized transmission maps for combinations of superlattices B-S and S-B.

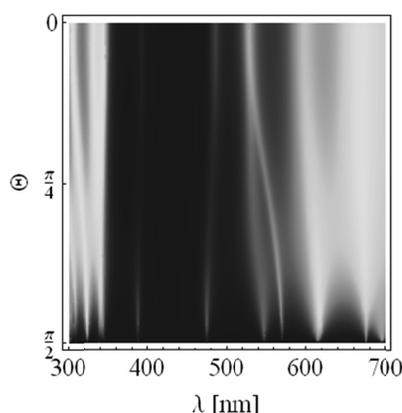


Fig. 18. Combination of S-B for $L=3$ and $n_B = -3.4$

3. Conclusions

The study lead to the conclusion that the transmission maps have a band structure depends on the polarization of the wave, have a fixed bands independent of polarization, B-TM and TM-B as well as for B-S and S-B show similar characteristics despite differences.

Combinations of B-S and S-B show a significant effect defects on the structure of superlattice transmission maps.

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