

Different Multi-layer Photonic Configurations for Light Filtering in Optical Communications

Rabiul Islam Sikder[†], Muhammad Fasih[†], Zunnoor Fayyaz Awan, Hyeonho Yoon, Hyo-Hoon Park, and Hamza Kurt

School of Electrical Engineering

Korea Advanced Institute of Science and Technology, Daejeon, South Korea

rabiulsikdereee@kaist.ac.kr, muhammad.fasih@kaist.ac.kr, zunnoor.awan@kaist.ac.kr, exhyho@kaist.ac.kr, parkhh@kaist.ac.kr, hamzakurt@kaist.ac.kr

Abstract— In this paper, we study the optical properties of periodic and quasiperiodic multi-layer configurations for light filtering in optical communications. The reflection spectrums of periodic and quasiperiodic multilayer structure are obtained using the finite-difference time-domain method. The optical filtering properties of the multi-layer structures are shown by comparing the reflection spectrum with the ITU-T dense wavelength division multiplexing standard.

Keywords— multi-layer structure, optical filter, quasiperiodic structure

I. INTRODUCTION

Photonic crystals are a class of periodic nanostructure with periodic dielectric indices. Light interaction with the photonic crystal causes a few forbidden frequency intervals to appear in the transmission spectrum which are named as photonic bandgaps. The transmission spectrums of the photonic crystals are studied in microwaves, terahertz and visible frequency intervals [1-3]. Optical waves with frequency equal to the photonic bandgap cannot propagate in the forward direction and thus gets reflected in the backward direction. The reflected components can be treated as a stopband filter in optical communication.

Recently, one-dimensional photonic crystals and their quasi-periodic version have shown excellent optical properties [4-10]. The multi-layer (1D) photonic crystal is considered as a common configuration in tuning the properties of optical devices. Therefore, they are considered as suitable alternatives for multichannel optical filters, low-loss waveguides, high reflectance mirrors, micro cavity and Omni guide fibers [11].

Among the various multi-layer photonic crystals, the periodic and quasiperiodic multi-layer configurations are considered because their transmission spectrums are dense in wavelengths. In this paper, we have studied the periodic and four quasi-periodic (Cantor, Fibonacci, Thue-Morse and Rudin-Shapiro) multi-layer photonic crystals for their potential application in optical dense wavelength division multiplexing (DWDM) filtering and multiplexing/de-multiplexing applications. The reflection spectrums were calculated using the FDTD method. We have studied the light filtering behaviour with free spectral range (FSR), number of narrow

bands and bandwidth of each band in the reflection spectrums by taking into consideration of the ITU-T standard.

Our work is organized as follows. In section II, an overview of different periodic and quasiperiodic multi-layer structures is presented. In section III, the reflection spectrums for different multilayer structures are provided. Finally, section IV concludes the article.

II. OVERVIEW OF DIFFERENT MULTI-LAYER CONFIGURATIONS

One-dimensional multi-layer structures consist of two different repeated alternating dielectric structures of layers A and B as shown in figure 1. The regular periodic structure has a period of $\Lambda = d_A + d_B$, where d_A and d_B are the thicknesses of layers A and B. To get maximum reflectivity of the central wavelength, quarter wavelength formula is used as $d_A = m\lambda_0/4n_A$ and $d_B = m\lambda_0/4n_B$, where n_A and n_B are the refractive indices of layers A and B, respectively, and m is an odd integer value [12].

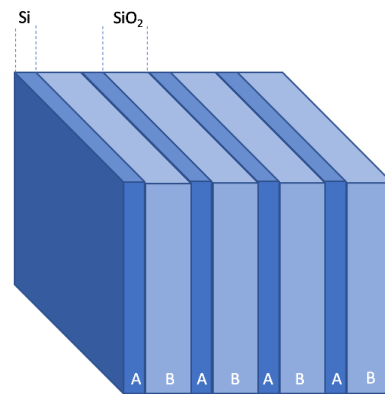


Figure 1. Regular 1D periodic dielectric structure

Quasiperiodic multi-layer structure consists of two layers of A and B which are arranged sequences of Cantor, Thue-Morse, Rudin Shapiro and Fibonacci. In quasiperiodic structures the layers are neither periodic nor random.

A one-dimensional Cantor quasicrystals consist of alternating binary letters, A and B. The structure is formed with dielectric layers, A and B in the pattern $A \rightarrow ABA$ and B

→ BBB [13]. The cantor sequence of third order is shown in Figure 2.

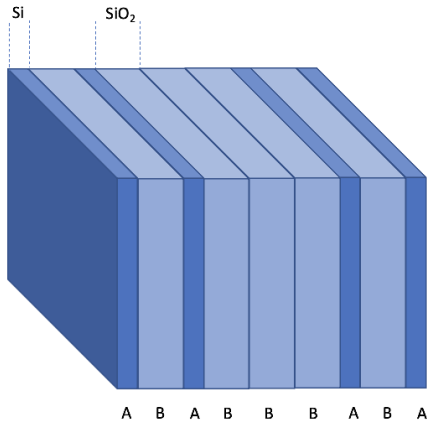


Figure 2. Schematic form of the Cantor sequence 1D multi-layer structure

The Rudin Shapiro sequence can be constructed starting with a four-letter alphabet. Starting with the letter A, the sequence expands by substituting $A \rightarrow AB$, $B \rightarrow AC$, $C \rightarrow DB$, and $D \rightarrow DC$ in the successive generations as given in Figure 3 [13].

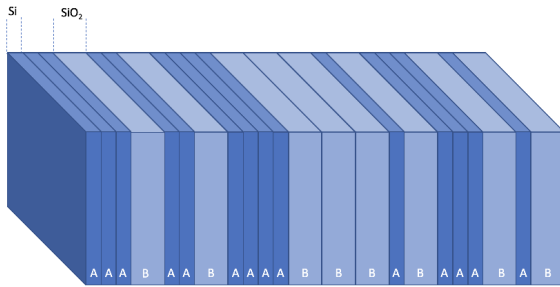


Figure 3. Schematic representation of the Rudin Shapiro sequence 1D multi-layer structure

The Thue-Morse sequence is the infinite sequence of binary numbers which is obtained by starting with 0 and adding the Boolean complement of the sequence in the next slot as shown in Figure 4.

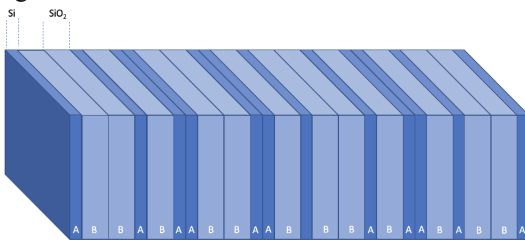


Figure 4. Schematic representation of the Thue-Morse sequence multi-layer structure

Finally, the Fibonacci structure is arranged according to the concatenation rule $S_{j+2} = S_j + S_{j+1}$ for $j \geq 0$ starting with $S_0 = B$

and $S_1 = A$, where S_j is the j th generation of Fibonacci structure. In Figure 5, the Fibonacci sequence of 5 is shown.

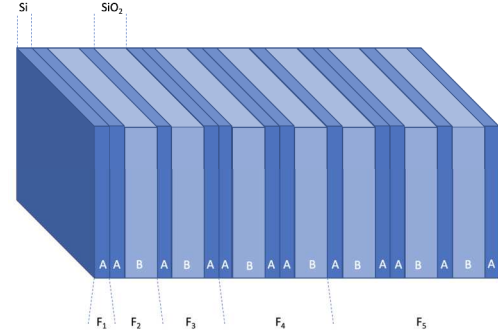


Figure 5. Schematic representation of the Fibonacci Sequence of 5.

III. REFLECTION SPECTRUM OF DIFFERENT MULTI-LAYER STRUCTURE

In this article, optical reflection bands of the multilayer structure, obtained using the FDTD method, are compared. In the reflection spectrum, a peak corresponds to a photonic bandgap or reflection band. In all the structures, we represent n_A , n_B , λ_0 , d_A , d_B , and D as the refractive index of layers A, refractive index of layer B, design wavelength, thickness of layer A, thickness of layer B, central wavelength, and length of the structure respectively. Layer A and B consist of silicon and silicon dioxide, respectively.

Figure 6 shows the reflection spectrum of a one-dimensional periodic structure which consists of alternating layers of A and B. A large number of filters is required for multiplexing/de-multiplexing a large number of channels. Moreover, the bandwidth of the reflected band is very wide, $\Delta\lambda \geq 850$ nm. The width of the reflection spectrum can be adjusted by playing with the number of the layers and refractive index contrast of the two layers.

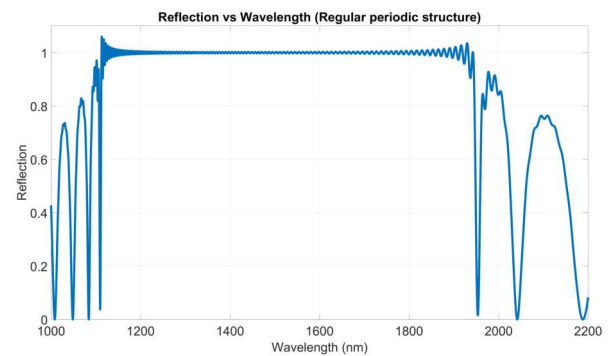


Figure 6. Reflection spectrum of regular periodic multi-layer structure

Figure 7 demonstrates the reflection spectrum of the multi-layer structure of the Thue-Morse sequence. The reflection spectrum consists of one single narrow-band. The bandwidth of the narrow-band is around $\Delta\lambda \geq 240$ nm which is smaller than the regular periodic multi-layer structure. However, it also contains only single reflected narrow band which requires

a large number of cascaded filter for multi-channel multiplexing/de-multiplexing.

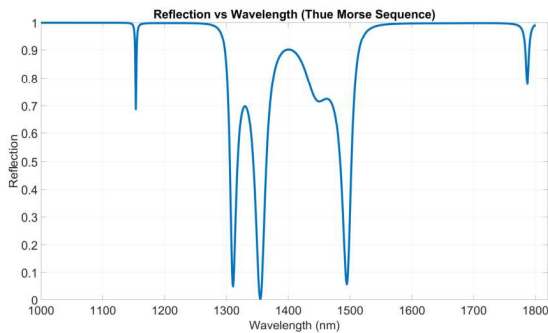


Figure 7. Reflection spectrum of Thue-Morse sequence multi-layer structure

Figure 8 gives the reflection spectrum of the multi-layer structure of Rudin-Shapiro sequence. It is evident that it contains multiple reflected bands. However, the reflected bands are not all similar in spectral shape. The bandwidth of the reflected band varies within $40 \text{ nm} \leq \Delta\lambda \leq 360 \text{ nm}$ and FSR is more than 40 nm.

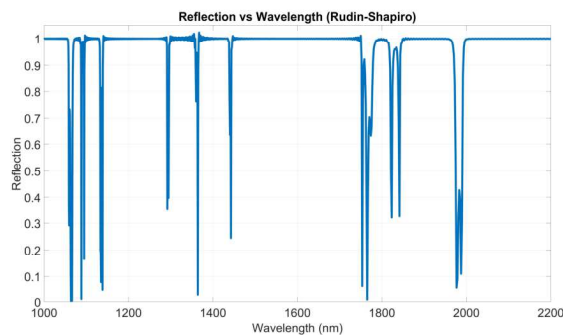


Figure 8. Reflection spectrum of Rudin-Shapiro sequence multi-layer structure

Figure 9 shows the reflection spectrum of the Cantor sequence multi-layer structure of order 3. It consists of several reflection bands of dissimilar shape. The bandwidth of each reflection band is $\Delta\lambda \geq 100 \text{ nm}$ and have FSR of around 25 nm. In addition to these, the power of each narrow reflected band is very low.

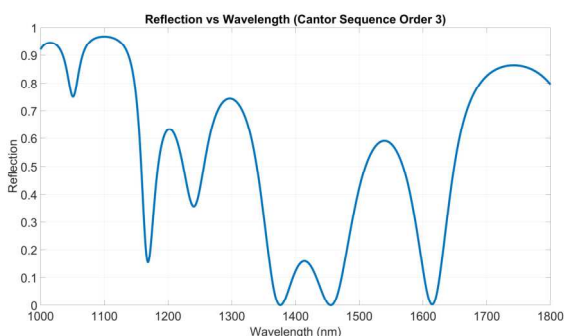


Figure 9. Reflection spectrum of Cantor sequence multi-layer structure (order of 3)

Next, Figure 10 shows the reflection spectrum of the multi-layer structure of Fibonacci sequence of 5. It contains two narrow reflected bands of bandwidth $\Delta\lambda \geq 100 \text{ nm}$ and the FSR is of around 120 nm. The shape of both the bands almost similar contains almost equal amount of power.

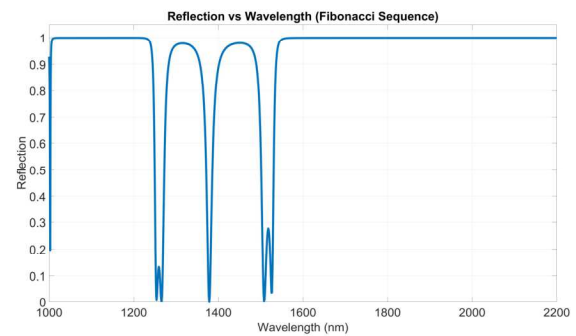


Figure 10. Reflection spectrum of Fibonacci multi-layer structure.

According to the ITU-T DWDM, the channel spacing between the two adjacent bands is 0.8 nm (100 GHz) or 0.4 nm (50 GHz). Table 1 shows the comparison of the reflection spectrum of the periodic and quasi-periodic multi-layer structure.

TABLE 1. COMPARISON OF THE REFLECTION SPECTRUM OF THE PERIODIC AND QUASIPERIODIC MULTI-LAYER STRUCTURE

Structure	FSR	Bandwidth $\Delta\lambda$	No. of reflected bands
Periodic	-	$\geq 850 \text{ nm}$	1
Thue-Morse	-	$\geq 240 \text{ nm}$	1
Rudin Shapiro	$\geq 40 \text{ nm}$	$40 \text{ nm} \leq \Delta\lambda \leq 360 \text{ nm}$	9
Cantor	$>25 \text{ nm}$	$\geq 100 \text{ nm}$	5
Fibonacci	$>120 \text{ nm}$	$\geq 100 \text{ nm}$	2

The higher number of reflected bands indicate that more wavelengths can be filtered out and reduced the number of cascaded filter to be used in DWDM fiber optic communication system. The optical filter in DWDM can be realized as shown in figure 11.

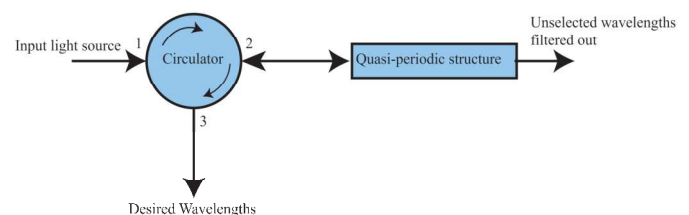


Figure 11. Optical filter in DWDM fiber optic communication system

IV. CONCLUSIONS

In this article, the reflection spectra of periodic and four well-known quasiperiodic (Thue-Morse, Rudin Shapiro, Cantor, and Fibonacci) structures have been obtained using the FDTD method and the comparisons of their spectra are

presented. We demonstrate the feasibility of our structures in optical filtering by comparing it with ITU-DTM standard. Although it is difficult to achieve the compatibility with ITU-T DWDM standard with the straight-forward design of these multi-layer structures, these comparisons will pave the way to achieving an optimized version of these multi-layer structure in the near-future work. The inverse design optimization with deep neural network may be an approach to achieve the desired metrics such as bandwidth, FSR and low cross-talk optical filters with these quasiperiodic multi-layers structures.

† THESE AUTHORS CONTRIBUTED EQUALLY.

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Rabiul Islam Sikder is currently a Ph.D. student at the Korea Advanced Institute of Science and Technology (KAIST). His research is focused on nano-photonics including the design and analysis of nano-phonic materials. He is also interested in the design and optimization of optical/photonic devices with traditional optimization algorithms and deep learning techniques



Muhammad Fasih received his M.S. degree in Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST) – Daejeon, Korea in August, 2019. His research focuses on silicon photonics, optical electronics and inverse design.



Zunnoor Fayyaz Awan is currently an undergraduate in electrical engineering at KAIST. His research focuses on the utilization of computational optimization techniques to enhance optical devices.



Hyeonho Yoon received Ph.D. degree in School of Electrical Engineering from KAIST (Korea Advanced Institute of Science and Technology), Korea, in 2019. He is now a research professor of Electrical Engineering, KAIST. His current research interests include silicon nanophotonics, 3D chip interconnection, optical phased-array antenna.



Hyo Hoon Park received M.S. and Ph.D. degree in department of Materials Science and Engineering from KAIST, Korea, in 1982 and 1985, respectively. From 1985 to 1986, he was a post-doctoral scholar from Stanford University. He was working for ETRI (Electronics Telecommunications Research Institute) since 1997. Since 1998, he is a professor of Electrical Engineering, KAIST. His current research interests include silicon nanophotonics for microprocessor-memory interfaces, 3D chip interconnection, phased-array antenna etc.



Hamza Kurt received his Ph.D. degree in Electrical and Computer Engineering from Georgia Institute of Technology - USA in 2006, and his M.S. degree in Electrical Engineering from University of Southern California - USA in 2002. He is currently a professor at the department of Electrical Engineering and director of MetaPhotonics Research Lab at KAIST – Daejeon, Korea