A Novel Procedure for Designing Band-pass Filters Using FSS Structures

Ge Wu, Volkert Hansen
Chair of Electromagnetic Theory, University Wuppertal
Rainer-Gruenter-Str. 21, D-42119 Wuppertal, Germany
Ernst Kreysa, Hans-Peter Gemuend
Max Planck Institute for Radioastronomy, Bonn, Germany

1 Abstract

In this paper, a novel design procedure for band-pass filters using frequency selective surfaces is presented. The connection to the classical filter theory makes it possible to develop a design method for the specification and the performance of FSS filters with a sharp filter slope and a good attenuation in the stop band.

2 Introduction

The frequency selective surfaces (FSS) embedded in layered media are applied as high frequency filters for astronomical investigations. The so-called capacitive grids, which are composed of infinite periodic array of patches on a dielectric support (polypropylene), are used as basis elements. The filters will be operated in the submillimetre wave range. They shall, on the one hand, exhibit a selectivity as high as possible; on the other hand, a broad stop band - a good attenuation is necessary particularly at higher frequencies because of the thermal radiation rising with f^2.

The design procedure consists of two main steps. It starts with a strict synthesis procedure of the classical filter theory for the development of filters with certain characteristics and their realization on the basis of lumped elements and transmission-lines, the equivalent circuits. For the second step a connection is established between the equivalent circuits and their realization as FSSs, in other words, the FSS filters, which consist of multi-layered patch structures of different patterns, are specified in such a way that their filter characteristics correspond to those of the equivalent circuits.

3 Realization of the band-pass filters from the capacitive grids

For the proposed astronomical experiments band-pass filters are required, which can be realized with inductive grids [1, 2]. However, for technological reasons only capacitive grids can be applied, which possess the characteristics of band-stops (Fig. 1).

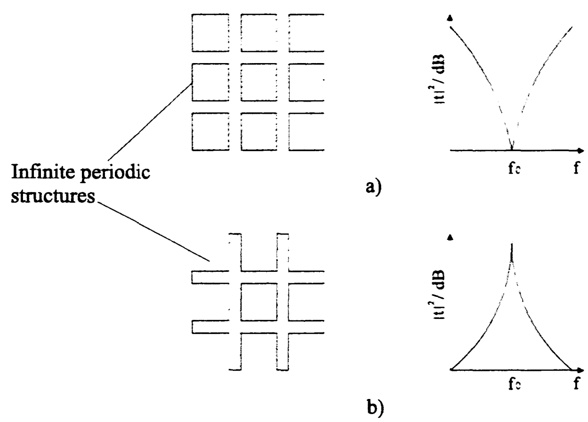


Fig. 1. Filter characteristics of a a) capacitive b) inductive grid

A solution is found by first developing a band-stop filter from capacitive grids and then connecting it to a high-pass. The resulting filter exhibits the characteristics of a band-pass in the frequency range up to the onset of diffraction. This combination is indicated in Fig. 2, schematically.

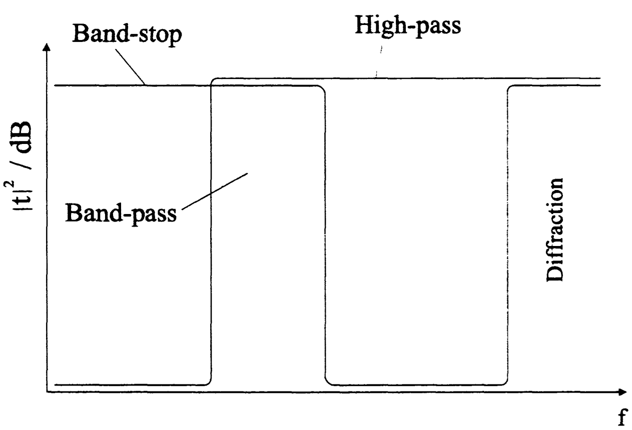


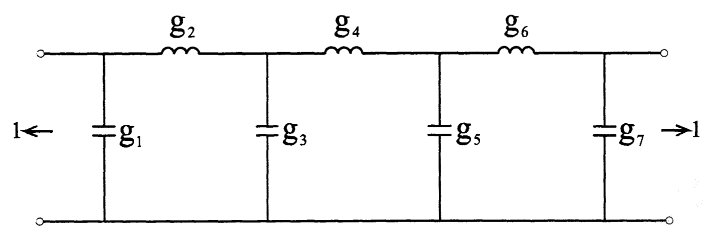
Fig. 2. Cascading of a high-pass and a band-stop

For the high-pass filter a circular waveguide is used. Because it is easy to design a circular waveguide, the entire problem is reduced to the task of developing the band-stop filters using capacitive grids.

4 Synthesis procedure of the classical filter theory

The approximation and synthesis of filter functions is one of the well-established problems in the communication technology ([3, 4, 5, 6]), i.e., the classical filter theory. The design of band-stop filters on the basis of lumped elements and transmission-lines is generally divided into the following steps:

It starts with a filter synthesis carried out in the so-called equivalent low-pass range. The filter slope and the attenuation can be entered as input data. The circuit obtained, the so-called Chebyshev low-pass, is composed of series inductors and shunt capacitors, i.e. an LC-network. The main parameters for specification are the degree of the filter, i.e. the number of the lumped elements, and the filter coefficients, which are obtained from tables given in the handbooks of filter design. The filter tables by Saal ([5]) are applied in this study. In Fig. 3, such a reference low-pass is indicated. It possesses the filter degree of 7 and the appropriate filter coefficients $g_1 \sim g_7$.



Filter coefficients: g_1= 0.535377, g_2=1.178914, g_3=1.463581, g_4=1.500080, g_5=1.463581, g_6=1.178914, g_7= 0.535377

Fig. 3. Equivalent low-pass of 7th degree with the filter coefficients

Fig. 4 shows the function of the so-called impedance inverter, which transforms a series inductor into a shunt capacitor.

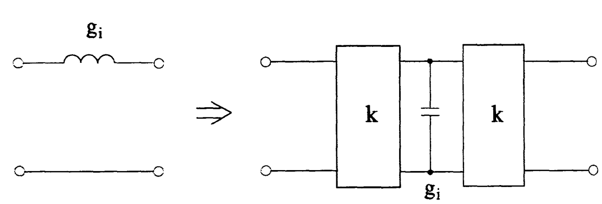


Fig. 4. Circuit transformation by the impedance inverter. k is the coupling factor

In the next step, the LC network we got in the first step, is transformed with the help of such impedance inverters into a circuit, which only contains shunt capacitors and impedance inverters (see Fig. 5).

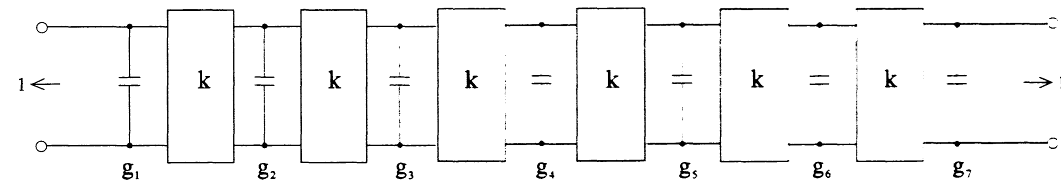


Fig. 5. Network with shunt capacitors and impedance inverters

In the third step, the low-pass is transformed into a band-stop using the low-pass / band-stop transformation (see Fig. 6a)).

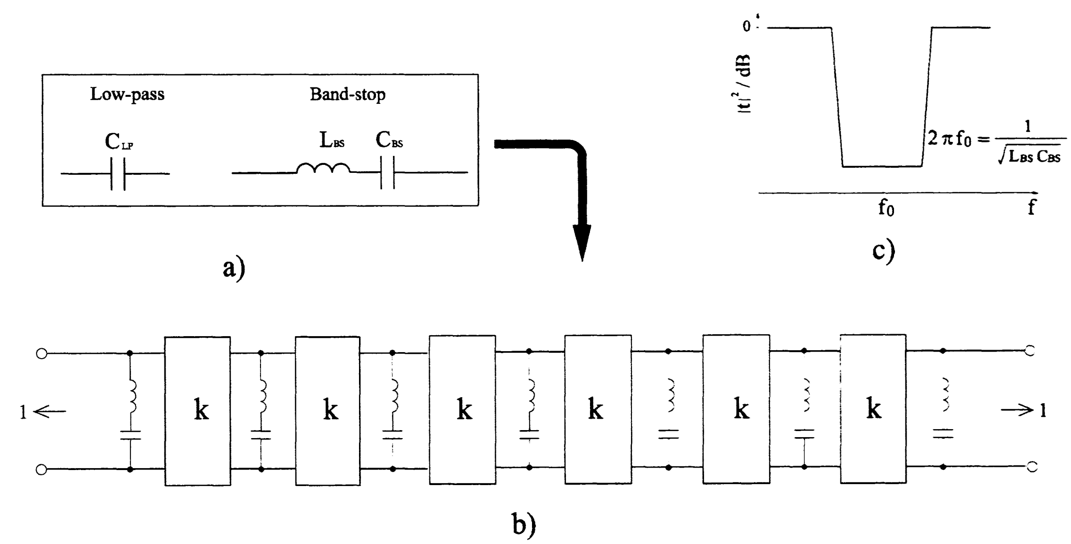


Fig. 6. a) Low-pass / band-stop transformation b) Network obtained after the Low-pass / band-stop transformation c) Filter characteristic of the band-stop

Now a band-stop filter is obtained, which is made up of the impedance inverters and series-resonant circuits in parallel (see Fig. 6b)). Fig. 6c) displays schematically the transmission character of the band-stop obtained, with the center frequency f_0.

Finally, as illustrated in Fig. 7, the impedance inverters are replaced by $\lambda/4$-transmission-lines, acting as impedance inverters. Thus we get a network, which contains series-resonant circuits connected by $\lambda/4$-transmission-lines.

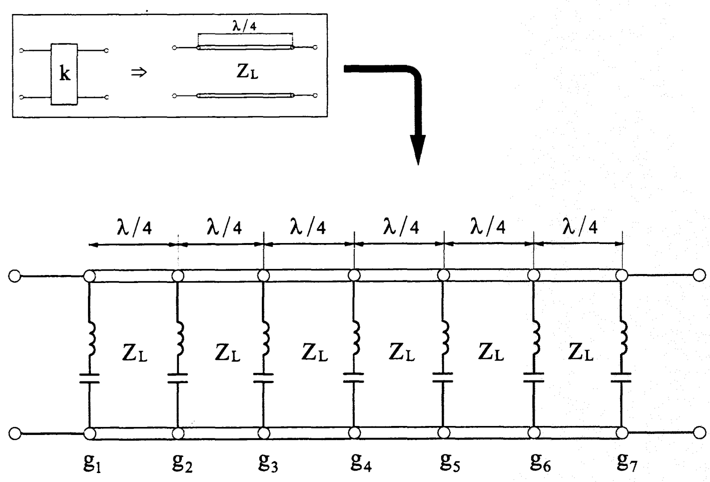


Fig. 7. Band-stop from series-resonant circuits connected by the $\lambda/4$-transmission-lines

5 Realization of the FSS filter

The transformation of the filter developed so far into an FSS structure starts with some well-known approximations ([7, 8, 9, 10]). As illustrated in Fig. 8, the $\lambda/4$-transmission-lines are first substituted by $\lambda/4$ dielectric layers. Then two additional layers of thickness $\lambda/2$ are attached above and below the FSS filter to provide a mechanical protection of the outer grids.

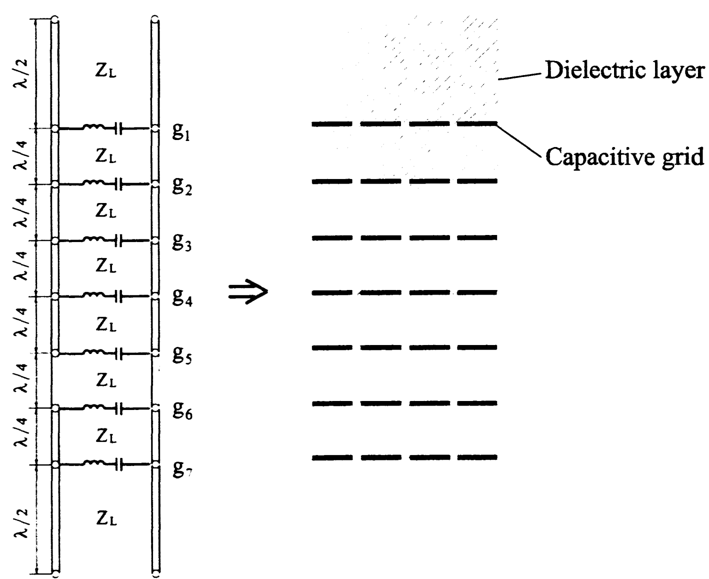


Fig. 8. Equivalent circuit model and the realization as FSS filter

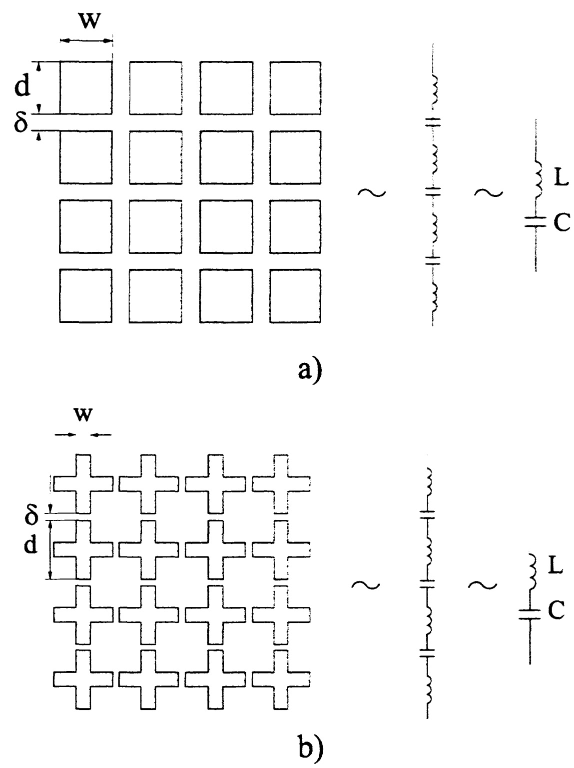


Fig. 9. Capacitive grid of a) square patch structure and b) cross dipole structure and their equivalent circuits as lumped elements

For the filters presented in this paper metallic square patches and crossed dipoles are applied as resonant structures. The geometries of these capacitive grids and their equivalent circuit as lumped elements are given in Fig. 9. Approximate design formulas available from literature are supplied as a starting point for the realization of the series-resonant circuits. For closely neighboring patches ($\delta/d \leq 0.2$), the formulations in [7]

$$L = \frac{A_L}{d\sqrt{w}} Z_0 \ [nH] \tag{1}$$

and

$$C = A_C d^3 \sqrt{w} / Z_0 \ [nF], \ A_L, A_C = constant, \tag{2}$$

are applied to derive the following proportionality

$$\frac{C_i}{C_j} \sim \frac{L_j}{L_i} \sim \frac{g_i}{g_j} \sim \sqrt{\frac{w_i}{w_j}}, \tag{3}$$

which is used for the specification of different FSS grids (here i and j) with the help of the existing filter coefficients (g_i and g_j).

Fig. 10 shows the structure of the FSS filter developed on the basis of the equivalent circuit model in Fig. 7.

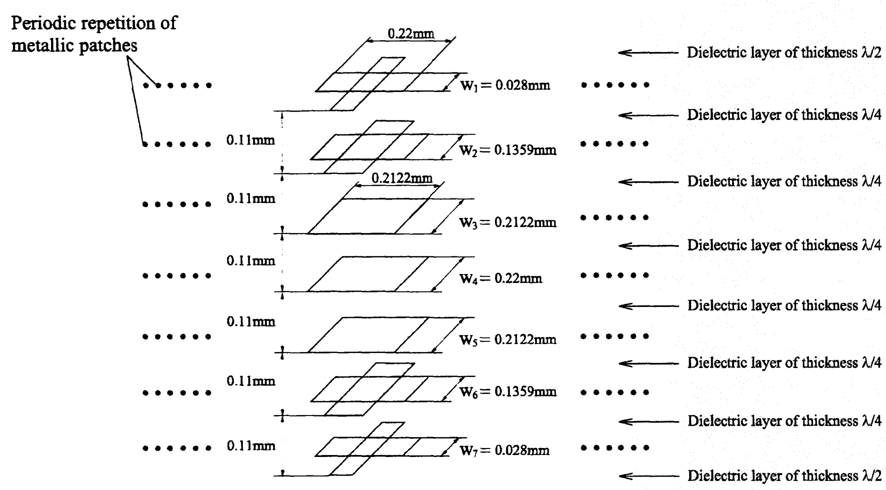


Fig. 10. Structure of an FSS filter of 7th degree from square patches and cross dipoles

The FSS structure obtained by this procedure is then analyzed with the below-mentioned numerical code. The performance of this first design is further improved by systematic variation of all design parameters.

6 Cascading of two or several filters

In order to further improve the band-stop character of the resulting filter, the diffraction will be suppressed or moved further to higher frequencies, respectively. This aim is partly achieved by the cascading of two or several band-stop filters, which corresponds to a shift of the diffraction range. Thus, a broader band-width of the resulting filter is provided.

7 Computation of the transmission factors

The transmission characteristics of the equivalent circuits are computed recursively starting from the end of the circuit with the help of the well-known transmission-line theory.

The computation of the FSS filters uses a spectral domain analysis based on an integral equation formulation applying the appropriate Green's function of layered media. The integral equation is solved by the method of moments combined with the Floquet theorem. A computer program on the basis of this theory has been developed. A lot of FSS structures have been calculated and a large number of measurements have been made, yielding a rather good agreement between the measured and the calculated values [11, 12].

8 Numerical results

In this section, some numerical results are presented, which first demonstrate the design steps according to the classical filter theory, and then show the correspondence between the equivalent circuits and the FSS filters. Fig. 11 shows the transmission factor of the filters of 7th degree, which work at the center frequency of 500GHz. For the filter slope the FSS filter and the circuit model are fairly in agreement. Further we get the result, that the FSS filter possesses a broader band-width and a greater attenuation in the stop band. This is because of the grating lobes phenomenon and the electromagnetic coupling within the structure. The curves of the filters of 11th degree with the center frequency of 500GHz are given in Fig. 12. These filters have a broader band-width and a larger attenuation compared with the filters of 7th degree. In Fig. 13, we demonstrate the cascading of 2 filters of 7th degree, which work at the center frequencies of 500GHz and 700GHz, respectively. The resulting filter possesses a much broader band-width in comparison with each single filter (see also Fig. 11).

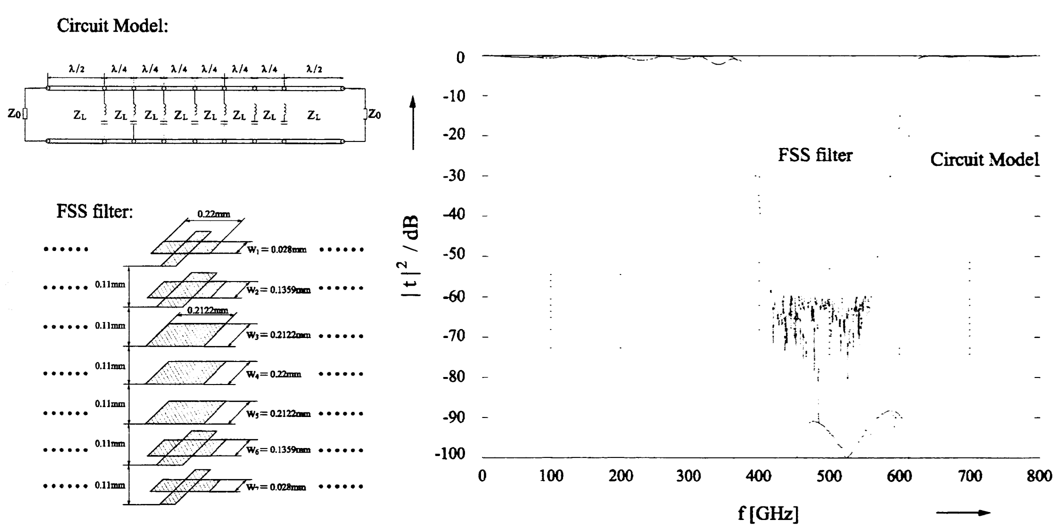


Fig. 11. Transmission characteristics of the circuit model and the FSS filter of 7th degree

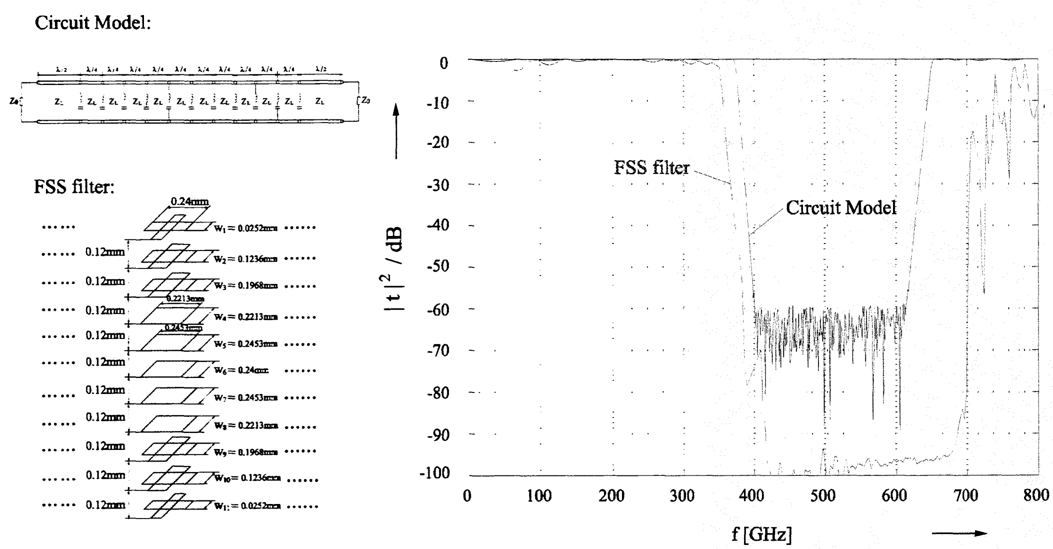


Fig. 12. Transmission characteristics of the circuit model and the FSS filter of 11th degree

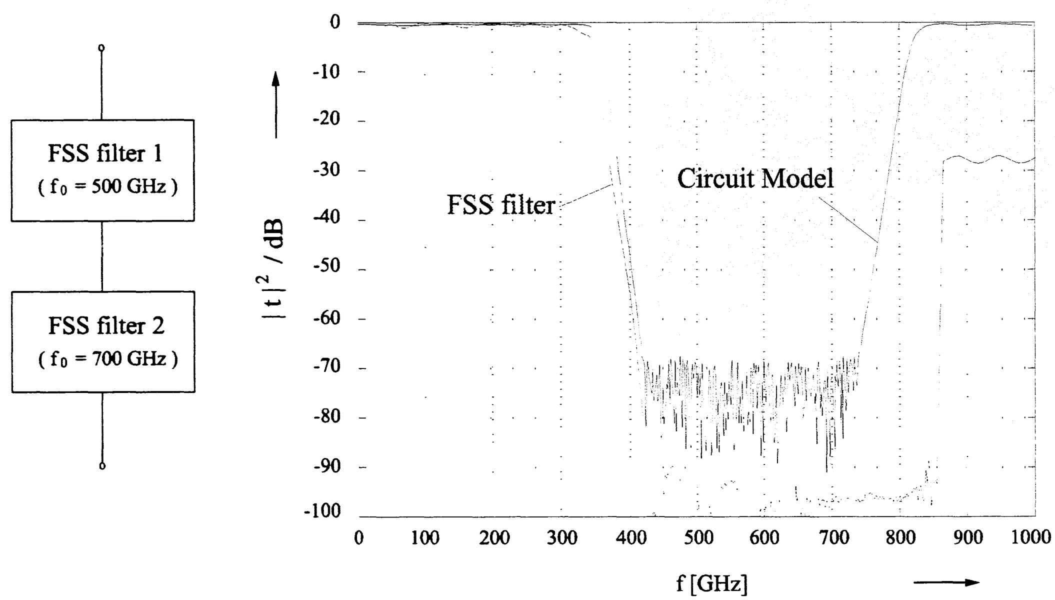


Fig. 13. Cascading of 2 FSS filters of 7th degree

9 Conclusion

With the help of the developed synthesis procedure it is possible to specify FSS filters consisting of a large number of layers. Therefore, the procedure is suitable for designing extremely complex filter structures in order to meet some special requirements. Up to now, filters with some ten layers have been investigated.

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