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A metamaterial based tunable terahertz bandpass filter and an algorithm to tune the resonant peak frequency

R A D S Abhijith , Nilotpal , Somak Bhattacharyya
Department of Electronics Engineering, Indian Institute of Technology (BHU),Varanasi, U.P.-221005, India.

Abstract

A tunable metamaterial based bandpass filter working in the terahertz frequency region has been proposed in this paper. The bandpass filter's resonant peak frequency can be adjusted to any value between 0.75 THz to 1.25 THz by varying a single dimension in the unit cell of the proposed structure. At this peak frequency, the structure offers a high transmissivity which is greater than 89%. The paper also presents an algorithm, developed and implemented in C++ platform to make the tuning process easy. The developed algorithm has a calculable upper bound over the number of trails required to tune the structure to a desired resonant peak frequency. The proposed filter is expected to find application in terahertz communication, imaging and sensing whereas the developed algorithm can find application in tuning any device where the desired property changes monotonically with respect to its variable.

1 Introduction

A metamaterial is an engineered material that gains its electromagnetic properties from variation in the shape and size of the subwavelength sized resonant metallic structures. During the last few years, there is growing interest in metamaterial-based devices due to their potential application as absorbers [1-2], filters [3-4] and polarization converters [5-6]. Recently, terahertz metamaterial filters have found significant interest in the research community due to their low profile and lightweight feature. One of the essential prerequisites for modern communications is the tunability of devices, since the next generation of systems operating at THz range requires operation over ultra-wide bands. Tunability of the devices is one of the most tedious tasks as it requires a lot of dimensional and structural iterations [7-9].

In this paper, a metamaterial-based tunable terahertz bandpass filter is reported. In our understanding, for the first time, a code has been written to achieve tunability for such devices. The resonant peak frequency can be obtained at any desired value between 0.75 THz to 1.25 THz by adjusting a single design dimension. The desired resonant peak frequency can be achieved by following a well-defined mathematical procedure that ends in a deterministic number of trails. The developed algorithm can be used for tuning many other devices just by making some minor changes in the code. The condition to use this algorithm is that the device's desired property should either decrease or increase monotonically with respect to one of the variables. Variable refers to any physical quantity in control of the designer that can vary between a range.

2 Design of the Structure

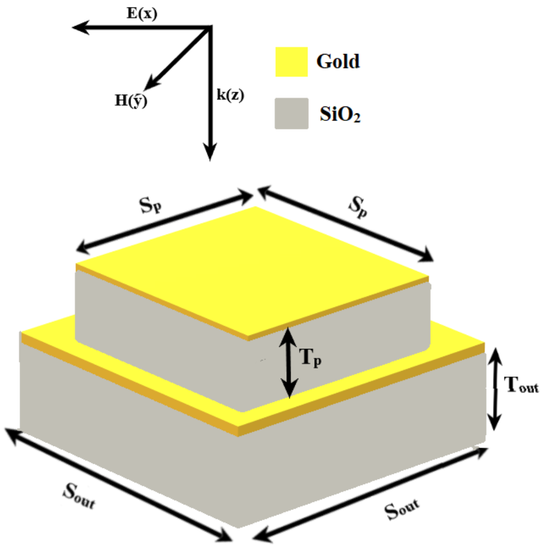

Figure 1. Proposed unit cell of the tunable terahertz metamaterial bandpass filter along with the incident electromagnetic field directions.

The unit cell of the proposed structure and the electromagnetic field direction are shown in the "Figure 1". The bottom part is SiO_2 (Silicon-di-oxide) as substrate with a side length of S_{out} and thickness of T_{out}. Another column of SiO_2 of side length S_p and thickness T_p is placed on the top of the bottom part. It is positioned so that the line joining the centres of both the cuboids is parallel to their thickness. The upper surface of the substrate together with the Silicon-di-oxide column, is covered with a thin layer of gold of thickness T_{gold}. The optimized dimensions of the structure are mentioned in "Table 1". All the simulations have been done in CST Microwave Studio considering periodic boundary conditions.

Table 1. Optimized dimensions of the proposed structure whose unit cell is shown in "Figure 1".

Parameter	Value
S_p	Variable (49-83 μm)
S_{out}	$1.3 * S_p$
T_{out}	$0.5 * S_p$
T_p	$0.25 * S_p$
T_{gold}	0.2 μm

3 Algorithm for Tuning

The algorithm for determining the proposed bandpass filter's resonant peak frequency has been discussed in detail below, along with the C++ implementation.

3.1 C++ Implementation

```cpp
#include<bits/stdc++.h>
#include<iomanip>
#define ld long double
using namespace std;

int main()
{
    ld lo        = 49.0000000000000000000000000;
    ld hi        = 83.0000000000000000000000000;
    ld mid,cut_mid,peak;
    ld lo_range =  0.75;
    ld hi_range =  1.25;

    cout<<"The Objective of this code is to facilitate tuning of
        centre frequency of a band pass filter at any particular
        value in the range "<<lo_range<<" to "<<hi_range<<endl
        ;

    cout<<endl<<"We determine the value of Sp at which the
        desired resonant peak frequency is achieved upto a
        precision of 2 digits after decimal in less than 8
        simulations . By uncommenting the commented lines, the
        same code can be used to achieve precision of n digits
        after the decimal in less than 2^(n+1) simulations "<<
        endl;

    cout<<endl<<"Enter the desired peak frequency(in Terahertz) (
        Range : "<<lo_range<<" to "<<hi_range<<" )    : "<<endl;

    cin>>peak;

    if(peak < lo_range  || peak > hi_range )
    {

        cout<<endl<<"You requested for a peak frequency that is
            out of the range of this structure "<<endl;

        return 0;
    }

    // cout<<endl<<"Enter the required precision in the form of
        number of digits after the decimal  : " <<endl;

    int pre=2;
    ld err = 1;

    // cin>>pre;


    for(int i=1;i<=pre;i++)
    {
        err = err /10.0;
    }



    while(hi-lo > err/1000.0 )
    {
        mid = (lo+hi) /2.0;

        cout<<endl<<"Please simulate the circuit by placing the
            Sp value as ";

        cout<<fixed<< setprecision (pre+4)<<mid<<endl;

        cout<<endl<<"Enter the value of peak frequency obtained
            upto a precision of "<<(pre+4)<<" digits : \n";

        cin>>cut_mid;

        if(cut_mid-peak < err  && cut_mid >= peak)
        {
            break;
        }

        if(peak < cut_mid)
            lo=mid;
        else
            hi=mid;
    }

    cout<<endl<<endl;
    cout<<"For value of Sp = ";
    cout<<fixed<< setprecision (pre+4)<<mid<<" ,"<<endl;
    cout<<"We obtain the centre frequency as ";
    cout<<fixed<< setprecision (pre+1)<<cut_mid<<endl;

    return 0;
}
```

3.2 Code Explanation

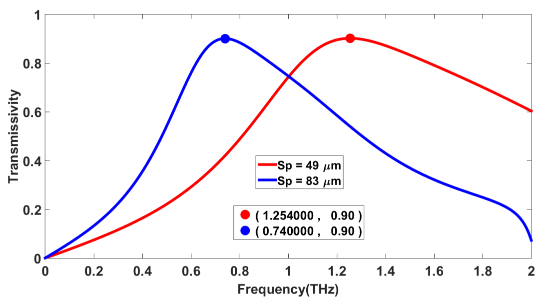

Figure 2. Transmissivity response of the proposed tunable terahertz metamaterial bandpass filter that helped in deciding the extremes of the tunable resonant peak frequency.

It is observed that varying the inner square's side length S_p (as shown in "Figure 1"), changes the bandpass filter's resonant peak frequency. When S_p = 83 μm, the peak is observed at 0.74 THz. On the other hand, a resonant peak frequency of 1.254 THz has been achieved for S_p = 49 μm.

The transmissivity responses can be seen in “Figure 2”, where the transmissivity at the resonant peak frequency is greater than 0.89. When S_p is between 49 µm to 83 µm, the centre frequency monotonically decreases from 1.25 THz to 0.75 THz, and every frequency value in this range can be achieved if S_p value is tuned correctly. This observation is the basis for the tuning algorithm developed in this section. This code is written using the binary search algorithm [10], which can be used on monotonic functions whose domain is the set of real numbers. This algorithm makes the tuning process easy and less laborious by finding the desired S_p value in less than $2^{(n+1)}$ trails, where n is the number of places in the desired frequency that has to be precise after the decimal. The most significant advantage is reaching the desired peak frequency accurately until a required number of places after the decimal and having a deterministic upper bound on the number of trails taken to reach.

The peak frequency at the mean of search space bounds is found to select either of the two halves as the next iteration search space. In the beginning, the bandpass filter’s peak frequency is found to be 0.934 THz at the mean value of search space bounds $(49+83)/2 = 66$ µm. If the desired peak frequency is greater than 0.934 THz, the right half of the search space is discarded, and the search space for the next iteration is 49-66 µm. If the desired peak frequency is less than 0.934 THz, the left half of the search space is discarded, and the search space for the next iteration is 66-83 µm. Since the set of real numbers is dense, it will not be possible to find the exact target value. So the search process is terminated when

$$mid - des < 10^{-(n+1)}$$

and

$$mid > des$$

where
mid = resonant peak frequency of bandpass filter when S_p is mean of the search space bounds,
des = Desired resonant peak frequency of the bandpass filter,
n = number of places that have to be precise after decimal.

4 Simulated Results

The bandpass filter’s resonant peak frequency can be adjusted to any value between 0.75 THz to 1.25 THz. As a demonstration, the simulations were made with the desired frequency of 0.81 THz with a precision of two places after the decimal. In this case, the desired resonant peak frequency is expected to be achieved in less than $2^{(2+1)} = 8$ trails where 2 in the exponent is the desired number of digits that has to be precise after the decimal.

The proposed unit cell is simulated using periodic boundary conditions in CST Microwave studio. “Figure 3” depicts that the tuning process started by providing the desired resonant peak frequency to the algorithm. The algorithm suggests that the designer simulate the structure by substituting

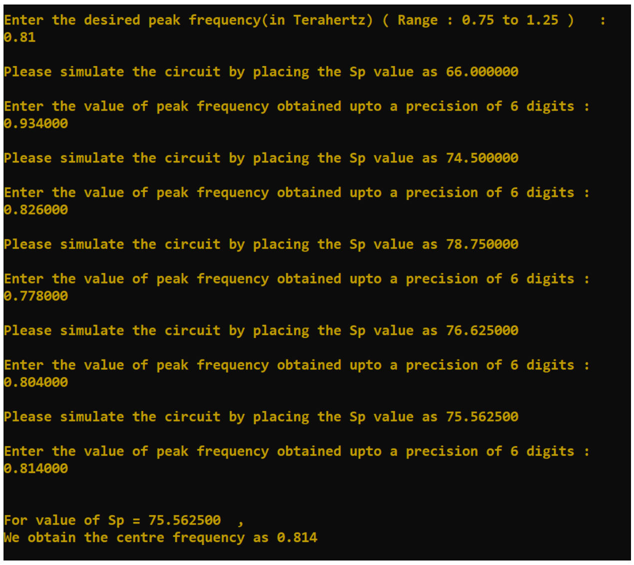

Figure 3. C++ compilation of the algorithm that aided the design in tuning the filter to a resonant peak frequency of 0.81 THz.

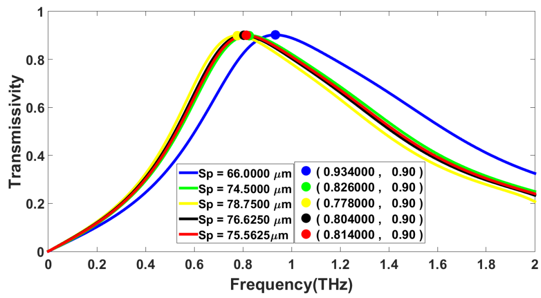

Figure 4. Transmissivity response of the tunable terahertz bandpass filter at 0.81 THz along with responses of all the intermediate states while tuning.

S_p as 66 µm and inputting the obtained peak frequency to the algorithm. It could be seen from “Figure 4”, that the peak frequency is obtained at 0.934000 THz when $S_p = 66$ µm. On providing the obtained peak frequency as an input to the algorithm, the designer is asked to simulate the design for an S_p value of 74.5 µm (as shown in “Figure 3”). The peak frequency is observed at 0.826000 THz (as shown in “Figure 4”). In the next step, the design is simulated for an S_p value of 78.75 µm (as shown in “Figure 3”) to obtain the peak frequency at 0.778000 THz (as shown in “Figure 4”). Then, the design is simulated for an S_p value of 76.625 µm (as shown in “Figure 3”) to obtain the peak frequency at 0.804000 THz (as shown in “Figure 4”). Finally, when $S_p = 75.5625$ µm, the peak is observed at 0.814000 THz which matches with 0.810000 THz until two digits after the decimal. The final desired structure is achieved in 5 simulations which is less than the expected maximum number of simulations (8 simulations). The procedure remains the same while tuning to any other value in the range of permitted frequencies but the upper bound on the number of trials required to achieve the desired peak frequency changes.

5 Conclusion

In summary, a tunable terahertz metamaterial bandpass filter is designed that is tunable to any value between 0.75 THz to 1.25 THz. An algorithm is developed and implemented to tune the filter to the desired frequency. The logic behind the algorithm is explained to clarify the conditions in which a similar approach can be used for tuning. A demonstration of designing a filter with the desired peak frequency of 0.81 THz is also reported. Transmissivity greater than 89% is observed at the peak frequency when the peak frequency is in its permissible range. It is possible to extend the permissible resonant peak frequency range further by improving the metasurface design, and the concept can easily be extended to other frequency ranges.

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