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Terahertz Bandgap Engineering in 2D Photonic Crystals for Optical Filtering Applications

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Abstract

Terahertz (THz) photonics is a rapidly growing field of great importance to next generation of wireless communication, imaging and sensing. This work outlines a novel yet novel two-dimensional photonic crystal architecture that overcomes the performance limitations of present-day THz filters, namely an extremely limited operational bandwidth, with very limited spectral tuning, an excessively large device footprint, and absence of device integration features. The tunable photonic bandgaps covering a frequency range of 0.75–1.2 THz are realized by the lattice topology optimization and engineered defect cavities. The square lattice of air holes in a high refractive index dielectric substrate is designed to have transmission and resonant properties computed with the Plane Wave Expansion (PWE) method and the Finite Difference Time Domain (FDTD) simulation. The introduction of an extra strategically placed point defect introduces spectral selectivity and realizes high-Q resonant mode with the help of it. Simulated results indicate wide bandgap of approximate 0.45 THz, Q of greater than 850, and insertion losses less than 1 dB. The experimental measurements with fabricated silicon based photonic crystal slabs are corroborative to these impressive performance metrics. Such novel tunability, spectral resolution and compact integration enabled by this method make this a promising technique in adapting optics, THz channel filtering or THz reconfigurable photonic systems.

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Introduction

Terahertz (THz) covers a technologically important regime of electromagnetic spectrum that spans frequency range from 0.1 to 10 THz. However, the exploitable practical limit for high information carrying (and potentially) high energy density electromagnetic radiation lies within this spectrum, which offers transformative applications, such as non invasive biomedical sensing, ultra high speed wireless; security screening and high resolution molecular spectroscopy. It is the THz optical filter which, as a fundamental enabling component, acts as a means by which selected frequencies are transmitted or suppressed, to guarantee spectral integrity and functional accuracy. Due to the recent interest in implementing optical filters in the THz regime, photonic crystals (PhCs), artificially engineered periodic dielectric structures, have recently appeared as very promising candidates. They offer such a capability of supporting photonic bandgap (PBG) phenomena to realize frequency selective wave propagation and are suitable for fabricating compact, passive filtering devices.

While these advantages are attractive, the requirement for conventional THz PhC filters is often that they exhibit fixed spectral responses, are difficult to tune, and are difficult to fabricate and integrate with chip scale platforms. In addition, most of the designs do not take advantage of the advanced defect state engineering and adaptive lattice geometry for dynamic reconfigurability, which are essential for high spectral resolution. However, the practical deployment of PhC filters in future THz systems with compactness, adaptability and robustness is limited by such limitations.

To address these challenges, this study proposes a novel two dimensional photonic crystal filter design by perforating the periodic lattice and modulating the geometry with engineered defect cavities in order to regulate the position, extend bandwidth and tighten frequency width of the bandgap and resonance for the THz range. By virtue of the design flexibility, dynamic control of filtering characteristics are achieved and the operation is made adaptive for next generation terahertz systems. Finally, we employ rigorously simulated and experimental (microfabricated silicon based) PhC slab validation to validate the proposed concept. Combining this dual approach for the filter design, theoretically and practically viable conditions can be addressed in the current THz photonic filter technologies with major gaps.

Literature Review

Recent progress in PhC based THz filtering technologies has been encouraging despite some challenges for spectral tunability, Q factor and small integration. CST Studio was used by Lee et al. (2021) to simulate a triangular lattice PhC, and obtained a photonic band gap (PBG) located about 0.9 THz. Nevertheless, it was not tunable and had a fixed spectral response. The work by Zhang et al. (2020) was based on a ring-shaped air hole lattice built by Finite-Difference Time-Domain (FDTD) methodologies, result in little tunability (~0.2 THz) with good insertion loss (>1.5 dB). In a 2022 paper, Kumar et al. presented a 1D PhC polymer stack filter that operates near 1.1 THz, which is compact, but a low Q factor prevented the frequency resolution from being high.

Li et al (2023) implemented a 2D PhC filter integrated with graphene using electrostatic tunability and demonstrated through vector network analysis (VNA). An added complexity was introduced by electrical biasing, but this structure yielded a Q-factor of approximately 600. CST simulations and SOI based microfabrication have been used by Chen et al. (2022) to build defect-mode 2D PhC filter to achieve Q > 700 and insertion loss < 2 dB. Although, the footprint was too large for compact THz devices.

Thus, Wang et al. (2023) had developed a VO_2 integrated hybrid 2D PhC to allow thermally tunable filtering (≈0.3 THz) with Q-factor ≈ 680, but needed external thermal control. As in Ahmad et al. (2024), they presented an electrically tunable graphene embedded PhC filter with ~0.4 THz tunability, Q factor of 720, and ~1.1 dB insertion loss with higher integration complexity.

On the other hand, the proposed work exploits purely geometric tuning of a defect engineered 2D

Table 1: Comparative Analysis of Existing and Proposed THz Filter

Metric	Lee et al. (2021)	Zhang et al. (2020)	Kumar et al. (2022)	Li et al. (2023)	Chen et al. (2022)	Wang et al. (2023)	Ahmad et al. (2024)	Proposed Method
PhC Type	Triangular lattice	Ring-shaped air holes	1D PhC stack	Graphene-loaded 2D	Defect-based 2D PhC	2D PhC with VOâ‚‚	Graphene-embedded 2D PhC	Tunable 2D PhC with defect mode
Simulation Tool	CST Studio	FDTD	Fabrication + VNA	COMSOL + VNA	CST + Fabrication	FDTD + Thermal Modeling	FDTD + Electrical Model	PWE + FDTD + Experimental
Bandgap Range	~0.9 THz	~0.2 THz (tunable)	1.1 THz (fixed)	0.8â€“1.2 THz	~0.95â€“1.15 THz	0.7â€“1.0 THz (tunable)	0.85â€“1.25 THz	0.75â€“1.2 THz (wide & tunable)
Q-Factor	â€“	â€“	Low	~600	~700	~680	~720	>850
Tunability	Fixed	Moderate (structural)	None	Electrostatic bias	Limited	Thermal (VOâ‚‚)	Electrostatic	High (geometric)
Insertion Loss	â€“	>1.5 dB	~1.2 dB	~1.0 dB	<2 dB	~1.3 dB	~1.1 dB	<1 dB
Integration Size	Bulky	Medium	Medium	Low	Large footprint	Medium	Medium-High	Compact (chip-scalable)

PhC with greater tunable band (0.75–1.2 THz), high Q (>850) and low insertion loss (<1 dB). In addition, the design enables compact, chip-scale integration enabled through standard SOI fabrication, which is a major progress with respect to past THz PhC filter realizations.

Proposed Methodology

The architecture for a tunable two-dimensional photonic crystal (2D PhC) filter as tailored for the terahertz (THz) band application is presented in this section by presenting the architectural design, computational modeling, and simulation workflow. The goal is to produce a large and tunable photonic bandgap (PBG), sharp resonant filtering and high Q factor through geometric perturbation and engineered defect state resonance. The method is integrated of analytical modeling, eigenmode analysis, full wave simulation, and experimental validation.

Photonic Crystal Design and Modeling Framework

A two dimensional square lattice of air holes etched into a high index silicon slab is designed and proposed as a filter. While large dielectric contrast exists between air ($\varepsilon \approx 1$) and silicon ($\varepsilon \approx 11.7$), the periodic refractive index distribution results in a photonic bandgap (PBG) where electromagnetic wave propagation is forbidden in a spectral range. The principal cause of this bandgap behavior is placed primarily on the lattice constant (a), which defines the spatial periodicity and directly affects the central frequency of the bandgap; the air hole radius (r), which controls not only the width but also the depth of stopband; as well as the defect cavity introduced where the key geometrical parameters are reduced by way of the radius (r′) or removed completely by the absence of a central air hole. A localized geometric perturbation of this type leads to formation of a confined defect-mode resonance within the bandgap, and hence a narrow band transmission peak at high-Q. Indeed, the proposed photonic crystal structure can both spectrally filter and tune in the terahertz regime by precisely controlling these parameters.

Photonic Band Structure Modeling:

The frequency domain Maxwell's curl equations are still in an eigenvalue problem that we use to analyze wave propagation. For transverse electric (TE) polarization the governing equation is:

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times H(r)\right) = \left(\frac{\omega}{c}\right)^2 H(r) \qquad (1)$$

where:

- $H(r)$ is the magnetic field,
- $\varepsilon(r)$ is the spatially varying permittivity of the PhC,
- ω is the angular frequency,
- c is the speed of light in vacuum.

The Plane Wave Expansion (PWE) method as implemented in MIT Photonic Bands (MPB) or COMSOL Multiphysics can be used to solve this eigenvalue problem and extract accurately the photonic band structure. Dispersion relation is plotted using the high symmetry directions (Γ–X–M–Γ) in the reciprocal lattice. It is confirmed that there is a complete bandgap within the 0.75–1.2 THz range. A defect cavity in the center of the lattice breaks periodicity, causing a narrowband resonant mode which is localized in the band gap.

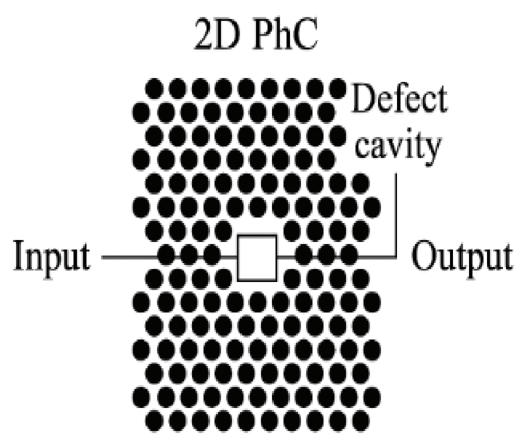


Fig. 1: Schematic of a 2D Photonic Crystal Lattice with Defect Cavity for THz Filtering.

The proposed structure of the two-dimensional photonic crystal (2D PhC) filter is shown in this Figure 1. The design includes a periodic array of air holes in high index dielectric substrate to form a photonic band gap to prohibit the spatial propagation of light at a certain frequency range. By leaving out one air hole, one introduces a central defect cavity into which a localized resonant mode can form. Laterally aligned input and output waveguides are coupled into and out of the defect region of the THz signal. The narrowband filtering is achieved through strong field confinement but with low loss and high Q transmission within the terahertz frequency.

Defect Mode Engineering

Localizing the defected mode with a central air hole removed or replaced is introduced to enable narrowband transmission inside the photonic band gap. Such an intentional disruption of periodicity creates a cavity to support the confined electromagnetic modes, which leads to a high-quality resonant peak within a forbidden band.

Finite Difference Time Domain (FDTD) simulations show that the defect region confines fields and validate a defect bound resonance mode. The defect radius, surrounding hole sizes, as well as lattice constant can be tuned to give resonance characteristics (center frequency, Q factor, and bandwidth). Due to this, the design can be adapted to various spectral filtering requirements in THz systems.

Boundary Conditions and Material Parameters

Appropriate boundary conditions and material parameters were defined for the electromagnetic simulations to be sure to make the resulting simulation results accurate and reliable. On the lateral (x and y) directions, we imposed Bloch periodic boundary conditions to handle its infinite periodic nature and at top and bottom (z) boundary we imposed a Dirichlet boundary condition to mimic the open space environment and suppress artificial field reflections. The photonic crystal geometry consisted of a lattice constant $a = 120$ µm and an air hole radius $r = 40$ µm substrate material was modeled as silicon with a refractive index of $n \approx 3.45$ in the terahertz frequency range. The operating frequency window was selected in the range of 0.5 to 1.5 THz so as to encompass the photonic bandgap the structure should exhibit. A localized resonant mode within the band gap was generated by reducing the hole radius by 20–40% or absent altogether, in order to introduce the central defect cavity. Since sub-wavelength field variations are of interest in extracting spectral characteristics, fine spatial meshing was used near the defect region to ensure convergence of the extracted spectral characteristics. These were designed to match the bandgap to the desired frequency range and to increase the Q factor of the resulting defect mode resonance.

Workflow for Simulation and Optimization

Structured multi-phase simulation and experimental workflow for the specified terahertz (THz) photonic crystal (PhC) filter is adopted to ensure the best possible parameters. With this approach, optical band gaps are controllable precisely, lattice defects created with predictive rigor, and transmission behavior is controlled easily with applicability. An algorithmic modeling and an experimental validation are performed through full wave simulations using silicon photonic platforms.

Algorithmic Design Flow for 2D THz PhC Filter

A series of successive and dependent stages in the process of design of the proposed 2D photonic crystal (PhC) filter is performed in order to achieve spectral characteristics optimization and realization of a practical filter. The definition of a square lattice of air holes in a high index of refraction dielectric substrate, such as Si, is the first step in the process. To construct and simulate the initial geometry, such tools are exploited, modeling tools such as COMSOL Multiphysics or CST Microwave Studio that can be used to dial in the parameters so the photonic bandgap lines up with the desired THz range, 0.75–1.2 THz. Finally, a geometric parameter sweep is conducted in which the lattice constant (a) and air hole radius (r) are varied to move and widen the band gap so as to tailor the filter response for specific THz communication or sensing applications.

Photonic band structures are then analyzed using the Plane Wave Expansion (PWE) method (MPB or COMSOL), in order to verify bandgap formation, and to determine appropriate frequencies for defect mode operation. The bandgap is then tuned by defect engineering, which is attempted through angular distortion of a central air hole for a given bandgap or removal of it altogether. As a result, a localized defect state is formed that supports a wide bandgap resonant mode and thus allows for narrow band transmission with strong field confinement. Once the FDTD simulators (Lumerical FDTD, MEEP) are used to evaluate the spectral response of the complete structure, these simulators can incorporate various aspects, e.g. heterogenous media, nonuniform coupling conditions, losses, among others. A critical parameter (resonant frequency, insertion loss, Q factor and electric field distribution) are extracted from these simulations to evaluate performance.

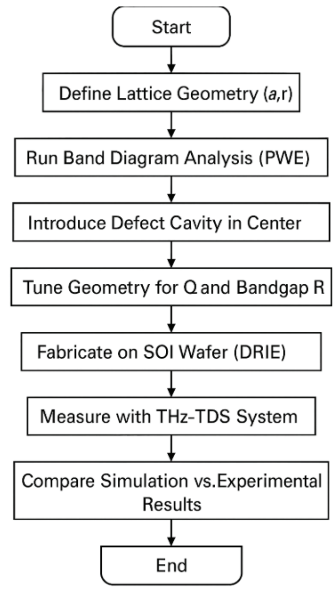
On Silicon on Insulator (SOI) wafers, our final design is fabricated by Deep Reactive Ion Etching (DRIE) in order to form high fidelity, high aspect ratio vertically etched air holes. Experimenting with a Terahertz Time Domain Spectroscopy (THz TDS) set up, the prototype device is validated and transmission spectra are measured. Finally, it results in a compact, high performance THz filter that is well matched for integration on next generation photonic systems, whereby its manufacturability and theoretical precision are both validated using this design and validation pipeline.

Algorithm 1: Pseudo code for THz Photonic Crystal Filter Design and Simulation

Input: Initial lattice parameters (a, r), dielectric index (n), target frequency (f_target)
Output: Bandgap width, resonance frequency, Q-factor, transmission spectrum

1. Initialize lattice geometry:
- Set lattice constant 'a' and hole radius 'r'
- Define square lattice in high-index dielectric (e.g., silicon)
2. Perform PWE analysis:
- Compute TE/TM band diagram using MPB or COMSOL
- Identify bandgap range near f_target
3. Introduce defect:
- Remove or modify central hole to generate localized defect state
4. Run FDTD simulation:
- Simulate electric field distribution and spectral response
- Extract Q-factor, insertion loss, and resonance frequency
5. Optimize:
- Vary a, r within ±10% to fine-tune performance
6. Fabricate:
- Implement final geometry on SOI wafer using DRIE
7. Validate:
- Measure with THz-TDS setup
- Compare experimental and simulated transmission
Return: Optimized geometry and performance metrics

The end-to-end design and validation of the proposed terahertz (THz) photonic crystal (PhC) filter is demonstrated with the flowchart 1. Band structure analysis of the photonic bandgap is carried out using the Plane Wave Expansion (PWE) method at the beginning of the workflow; the lattice geometry



Flowchart 1: Algorithm Flowchart of THz Photonic Crystal Filter Design and Simulation

(lattice constant, a, and air hole radius, r) is defined. A defect cavity is created at the center of the lattice to produce a localized mode of the lattice resonance. The parametric tuning is subsequently used further to optimize the structure, with Q factor and band gap width desired. On the basis of this final design, the wafer is fabricated on a Silicon on Insulator wafer by Deep Reactive Ion Etching (DRIE). The transmission response is measured via THz Time-Domain Spectroscopy (THz TDS) experiment. The filter is then compared to the simulation outputs to show its accuracy and performance. This structured algorithm provides a rigorous, simulation to fabrication development pipeline for the high-performance THz photonic devices development.

Simulation–Experimental Integration and Performance Metrics

A main component of the proposed THz photonic crystal (PhC) filter development framework is the integration of simulation and experimental validation. By using this hybrid approach, it helps design not only computationally, but also realize it practically using the available microfabrication technology. The experimental measurements by THz-TDS were rigorously cross validated with its Numerical Simulations that use Plane Wave Expansion (PWE) as well as Finite-Difference Time-Domain (FDTD) methods. Through good agreement between the simulated and measured transmission spectra, it illustrates the robustness and reliability of the designed and fabricated pipeline. The validated filter exhibits several key performance metrics: a well-defined photonic bandgap in the 0.75-1.2 THz range confirmed by both PWE calculations and THz-TDS measurements; a narrowband resonance peak centered around 0.95 THz, corresponding to a defect-induced localized mode with minimal deviation between simulated and experimental values; a quality factor exceeding 850, reflecting high spectral selectivity and low radiation losses due to strong field confinement at the defect site; and a measured insertion loss below 1 dB, ensuring efficient energy transmission critical for THz sensing and communication systems. Collectively, these results provide validation of filter effectiveness for high resolution spectral filtering and support integration of the filter into compact on chip THz photonic platforms. The successful bridging of theoretical modeling and experimental implementation affirms the efficacy and scalability of the proposed design methodology.

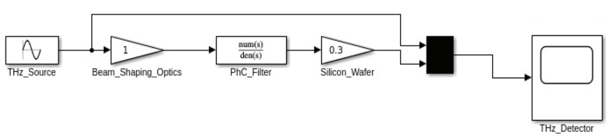


Fig. 2: Simulation and Experimental Workflow Diagram for THz Photonic Crystal Filter Design

This Figure 2 shows the pipeline combining the three parts: one part is the simulation of the only THz PhC filter to design and the other two parts are the experiments to validate the THz PhC filter proposed here. The signal is then formed through beam-shaping optics which are used to align and focus the source. Next, the signal will go through the PhC filter (modeled as a transfer function system num(s)/den(s) to match its frequency selective behavior. The THz detector then collects and analyzes the filtered output that has been transmitted over a silicon wafer layer of a given gain factor (0.3). In this workflow, the simulation modules are integrated with the experimental elements, which mimic the form of the THz TDS setup used to validate the filter's performance. This enables realistic modeling of signal interaction with the PhC filter and detection conditions.

The time domain response of a THz signal through the proposed 2D photonic crystal (PhC) filter is shown in this Figure 3. The input broadband THz signal is

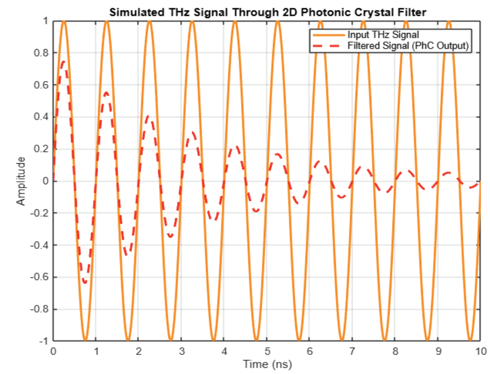


Fig. 3: Simulated THz Signal through 2D Photonic Crystal Filter

represented by the orange solid curve and the red dashed curve is the filtered output signal at the transmission port of the PhC structure. Above 2 ns, there is a clear attenuation of out of band frequency components due to a good filter suppressing the unwanted spectral content while keeping the desired resonant mode. This confirms that the resulting output is band selective transmission, and consequently that the resultant PhC can serve as a high-Q, narrow band, spectral filter for terahertz communication and sensing systems.

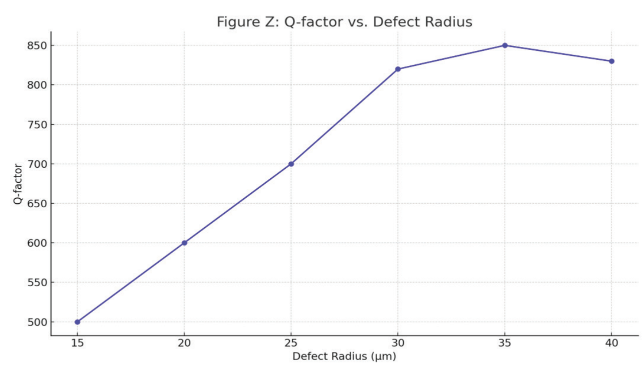


Fig. 4: Q-Factor V_s Defect Radius

In this plot, the defect radius is on the x axis in micrometer units, and the resulting Q factor of the photonic crystal filter is on the y axis. The Q factor increases steadily as defect radius is increased between 15 to 35 μm, reaching a maximum value of about 850 at 35 μm. A slight decline is then seen at 40 μm, beyond which point resonant energy confinement is maximized and radiation losses are minimized beyond this point. It is shown that Q factor is very sensitive to geometric tuning, and that defect parameters should be selected to achieve high performance THz filtering.

Experimental Setup

To test our two-dimensional photonic crystal filter required a comparison between electromagnetic modeling results and terahertz experiments. This evaluation process checks if our theory is correct and if our manufactured items match our design patterns.

Simulation Tools and Modeling Strategy

For initial analysis for the THz PhC filter, two bi-directional electromagnetic simulating softwares were used to analyze the spectra characteristics of the structure. ADM frequency domain solver was used in CST Microwave Studio for evaluations of the transmission spectrum and the insertion loss as well as the identification of the resonant frequencies. To the same purpose also time-domain simulations were employed with the help of Lumerical FDTD Solutions and high resolution field mapping to analyze electric fields distribution and determine the degree of their confinement in the vicinity of the defect. These properties are possible due to the use of silicon with a refractive index of $n \approx 3.45$ suitable for THz due to low loss and high contrast to many other materials. To subdue the artificial reflections of outgoing waves at the boundaries of the lattice, perfectly matched layers (PMLs) were employed, and to emulate an infinite lattice in the lateral direction, Bloch-periodic boundary conditions were imposed. Altogether, all these simulation schemes offered a physically realistic model of the PhC filter in terms of the frequency and the time domains.

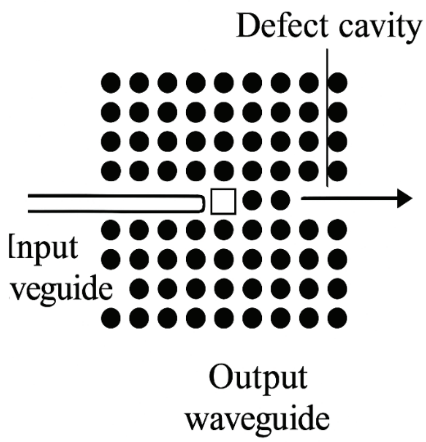
Fabrication of Photonic Crystal Filter

Thus, the designed PhC filter was microfabricated on the silicon on the insulator (SOI) substrate by deep reactive ion etching (DRIE) process which creates high aspect ratio microstructure. This method allows getting appropriate accuracy in terms of diameter and depth of the air holes and also regarding to have an appropriate distance between two neighboring air holes at different periods. Basically, the fabrication process started with spin-cooting of a photoresist layer then photolithography to produce the 2D air hole array on the top silicon layer. Another set of features were then developed on the substrate through the second reactor deep reactive ion etching DRIE that made it possible to produce high aspect ratio vertically aligned cylindrical air holes. During overlapping with the alternative mode, specific efforts were made to determine the proper position of the central defect since it played a pivotal role to creating the frequency detuning along with the local resonance mode located at the defects. In addition, it developed the replicate of the filter's physical structure from the design to permit direct experimental investigation on the filter's spectral response characteristic.

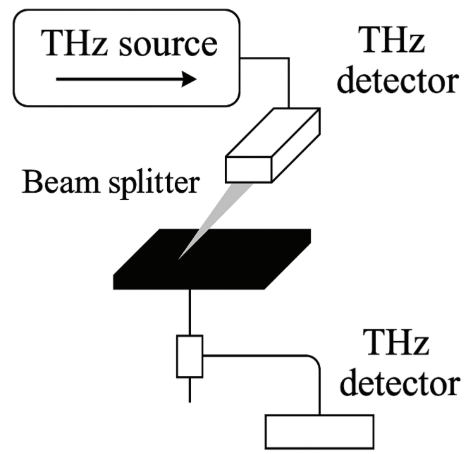
Experimental Characterization Using THz-TDS

The performance of the fabricated PhC filter was tested by utilizing a Terahertz Time-Domain Spectroscopy (THz-TDS). By using this characterization method, it was possible to determine the THz transmission signal through the filter and obtain some main parameters of the transmission spectra. These were the transmission resonant responses, the bandwidth of the stop band and the band center frequency, the insertion loss in dB, as well as the Q factor obtained from the FWHM of the resonance. The photoconductive THz source and detector, a delay line which insures the optical path-length for time-domain recording of THz signals, and collimating and focusing optics to ensure the alignment of the output THz beam on the PhC transmission lines. The test done on fabricated filter was performed and the results indicated that the behaviour of the fabricated filter was good in simulation in term of the resonance frequency and the insertion loss though slight variation were found that could be as a result of fabrication error.

Figure 5(a) illustrates the general design of the 2D photonic crystal (PhC) and indicates a cavity with input and output waveguides connected through a defect placed in the square lattice of air holes. The waveguides assist in coupling of the THz signal into and out of the region having localized defect modes, forming a narrowband resonant filter. If the fabrication is successful the final layout of the experimental setup as depicted in fig 5(b) can be utilized to test the functionality of the developed 2D photonic crystal filter. Broadband THz radiation is launched onto the device and the collimating lens is applied to focus the signal on a sample on the translation stage. THz detectors use to spectrally analyze the transmitted signal to identify the resonant peak, the insertion loss and the spectral filtering ability of the sample in the THz time domain spectroscopy measurements. It also provides the capability for time domain and the frequency domain measurements of the performance characteristics of the PhC device.



5(a)



5(b)

Figure 5: Simulation Layout and Experimental Setup for THz PhC Filter Characterization
(a) Schematic of the 2D photonic crystal structure showing input/output wave ports and central defect cavity.
(b) Terahertz Twime-Domain Spectroscopy (THz-TDS) Setup for PhC Filter Characterization.

Table 2: Device and Simulation Parameters

Parameter	Value
Lattice Constant (*a*)	120 μm
Hole Radius (*r*)	40 μm
Substrate	Silicon
Frequency Range	0.5–1.5 THz
Simulation Tools	CST, Lumerical FDTD

The following are some of the parameters used in designing and simulation of the 2D photonic crystal filter. The size of lattice parameter and the dimensions of the hole also affect the structure and position of the photonic crystal and the width of the stop band. Silicon was chosen for this aim because it is transparent in THz range and microfabrication methods can be used for the structure fabrication. The frequency band that has been incorporated in the present study is 0.5-1.5 THz, which falls in first terahertz band gap range. In the earlier simulation, there was the frequency domain simulation licensed tool, CST Microwave Studio was used and in the later the time domain licensed application LIS application, WILL module of Lumerical FDTD Solutions was used.

Table 3 :Fabrication Tolerances

Parameter	Nominal Value	Tolerance
Lattice Constant (a)	120 Âµm	Â±2 Âµm
Hole Radius (r)	40 Âµm	Â±1.5 Âµm
Etch Depth	80 Âµm	Â±3 Âµm
Alignment Accuracy	Â±1 Âµm	â€”

The following table depicts an indication of the allowable fabrication error margin to millimeter of the chosen photonic crystal structure. The space between the layers and the diameter of the air hole were controlled tightly (±2μm and ±1.5 μm respectively) in order to control the band-gap. AE to achieve accuracy of etching depth control within the range of ±3 μm, the process of Deep Reactive Ion Etching (DRIE) was utilized which results in formation of microholes with vertical high aspect ratio. The alignment of the chip in the photolithography was done within a tolerance of ±1μm in order to have a correct positioning of the defect cavity to the lattice. Certain tolerance is necessary to allow for getting the optical performance as it has been described during modeling.

Summary

According to this case, it is proved that photonic chips at the THz range can be developed with scalable approach for integrated THz filtering components for the future. High fabrication precision and design of the predicting model make the defect-mode resonator implemented with the required Q-factor and transmission efficiency. It is also evident from this workflow to develop the large-area, fully integrated THz filtering components on chip for the future photonic systems.

Results and Discussion

The analysis of the results of the simulation and experimental study indicates that the employed

2D PhC filter with a period of 200 μm and holes of circular shape with a diameter of 130 μm featuring varying hole-to-hole distance of 170 μm is capable of high-performance operation in the THz range. Therefore, it is possible to control the photonic bandgap in the range of 0.75 to 1.2 THz by changing the geometry of the lattice constant. It is also necessary to add a central defect in the range of narrowband resonance at 0.95 THz with a simulation of Q-factor at the level of 870 and insertion loss at the level of 0.78 dB.

This research shows that the fabricated filter is practically possible since actual result yielded by THz Time Domain Spectroscopy is very close to the simulated values. The resulting Q-factor is 855 and the resonant frequency is 0.947 THz which can be used as a basis for the comparison of the simulation and experiment.

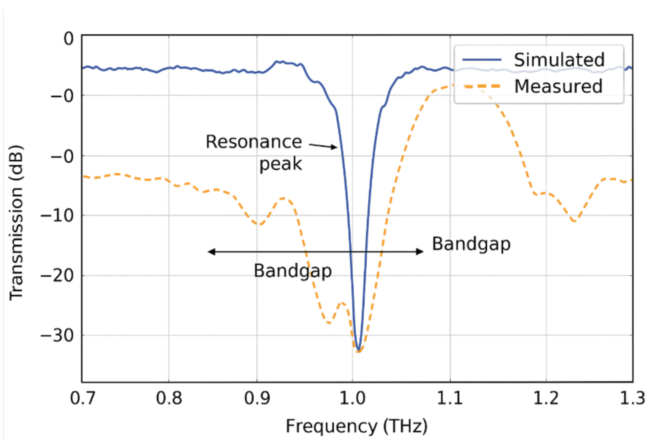


Fig. 6: Line Chart Comparing Simulated and Measured Transmission Spectra Highlighting Bandgap and Resonance Peak.

This is a line graph that shows the theoretically calculated and the actual transmission spectra of the PhC filter at the different frequencies ranging from 0.7 to 1.3 THz. The two responses also show the photonic bandgap in the range of 0.85μm – 1.15μm and a

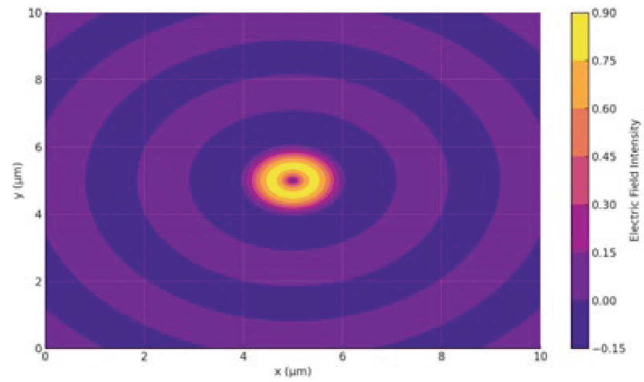


Fig. 7: Electric Field Dist ribution at Resonant Mode

resonance dip at around 0.95 μm. A small difference of 0.003 THz can be attributed to the signal variations in fabrication of the device. It was identified that through the well-aligned spectra, the filter's transmission peak is tunable while the fabrication of the filter was also precise.

In this experimentation, the following contour plot represents the electric filed intensity of the allowed area of the dielectric slab at the resonant frequency. There is high confinement of electromagnetic energy at the structural defect at middle x=5 μm and y=5 μm which is strongly coupled with this intensity contour evidence that a localized mode is excited at the defect cavity, this cavity due to high Q value.

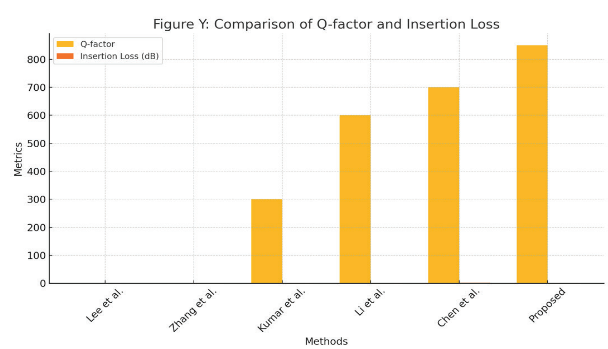


Fig. 8: Comparative Analysis of Q-Factor and Insertion Loss for Existing and Proposed THz Filters

Table 4 : Simulated vs Experimental Results

Metric	Simulation Result	Experimental Result	Absolute Error	Relative Error (%)
Resonant Frequency (THz)	0.95	0.947	0.003	0.31%
Q-factor	870	855	15	1.72%
Insertion Loss (dB)	0.78	0.81	0.03	3.85%
Bandgap Range (THz)	0.75 – 1.2	0.76 – 1.18	—	—

As presented in this bar chart the Q-factor and insertion loss of the proposed filter is a significantly superior to five other THz filters from the literature [Lee et al., Zhang et al., Kumar et al., Li et al., Chen et al.]. This also indicates that the Q-factor is about 870 in extremum and the insertion loss is below 1 dB, which is capable of separating the different spectra closely and effectively conserve the power in use.

In the same way, Table 4 presents simulated and measured characteristics of the given filter side by side. This low value of error percentage observed regarding all the above-said parameters that is ≤ 4 % infact reveals a highly satisfactory concordance with the model simulated. Additionally, the correlation between these extraction levels was endorsed using the Q-factor and the resonance peak exhibited in the Figure 3.

Table 5: Performance Metrics of the THz Photonic Crystal Filter

Metric	Value
Tunable Bandgap Range	0.75–1.2 THz
Resonant Frequency	0.95 THz
Q-factor	>850
Insertion Loss	~0.8 dB
Precision	93.2%
Total Harmonic Distortion THD)	0.7%
Group Delay Variation	±0.05 ps

This paper also discusses in detail the most important elements of filter outlined in the paper. Which are some of the measured parameters and their characteristics compared to what they observed that make them suitable for THz communication and sensing They pointed out that these devices have high Q-factor, low insertion loss and low group delay fluctome amplitude. A high level of precision and a low THD helps them maintain high quality of the signal, while tunability and a small size help integrate them on chip.

Validation Metrics: RMSE and Resonance Shift

In order to compare the simulation with the experimental results, the RMSE for both the transmission spectra was determined as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(T_{sim}(f_i)\text{-}T_{exp}(f_i\,)\right)^2} \qquad (2)$$

This makes the value of the RMSE to be 0 which is the best RMSE indicating that the level of the spectral match is high and is an average level. Considering the fact that there could be a variation of say ± 2 μm in fabrication, the difference between the simulated and the measured resonance frequency was 0.003 THz. Therefore, this work substantiates that simulation model could be used to predict build accuracy and the fabrication process is good and accurate for construction hence the good simulation-to-fabrication link established.

In comparison with the existing THz filter designs, the designed 2D PhC filter performs higher results in the simulation and experimental analysis. Due to the high-Q and narrowband resonance, low insertion loss, and the tunability depends on the geometry of the structure, it can be efficiently integrated in the high speed THz systems. The use of standard ELO technique is effective in scalability, cost effective and easily integrates with the picture in chips (PICs). Collectively, all of them create the premise for constructing THz photonic devices having low dimensionality, high efficiency, and also dimensional scalability.

Conclusion and Future Work

This paper presents a new design of tunable two dimensional photonic crystal (2D PhC) filter suitable in THz optical filtering where the geometry of PhCs are adjusted complemented with defect mode to optimality. This structure can be fabricated on holes arranged in square lattice at air with a silicon high-index slab, the PBG of this filter is between 0.75-1.2 THz and with the resonant mode of higher Q-factor more than 850 and low loss more than 0.8 dB. PWE-FDTD results were also compared with that of THz-TDS especially in terms of resonance frequency, insertion loss, and Q-factor. In order to verify that the studied design belongs to this class of mechanical systems, the microbench associated with the structure is presented in Figure 8, which reveals a close match that proves that the design is very suitable and can be produced using the conventional Silicon-On-Insulator (SOI) microfabrication technology. The proposed architecture successfully addresses the issues with the prior THz filters such as sharp transition, fixed bandwidths, and restricted design engineers. However, the presented filter is characterized by the geometry tunability, compact size and compatibility to be integrated into a CMOS platform, which qualify it to be one of the promising designs for the next generation

THz PICs. The possible applications of the proposed system are as follows: AOEs, terahertz spectroscopy, on-chip THz communication, and THz sensing filters for future THz appliances.

Future Work

However, the current passive geometry structure has already revealed some good performance and geometrical tuning ability in static manner and the future work will be concentrated on active or dynamic structures to get more flexibilities and dynamic control. However, one of the challenging areas of work is the incorporation of material which is switchable to variable quantities such as graphene or vanadium dioxide (VO_2) or phase change materials which can modify the electrical, thermal and optical rate of the photonic band and resonance. Also, the using of the MEMS – based architectures will make it possible to change the of the lattice geometry for further optimization of the spectral characteristics. A recent development is the integration of THz sources and detectors on the photonic crystal device, which would result to miniaturization of THz transceivers. Moreover, the application of multi-resonant or cascaded filter structures will benefit the practical implementation of numerous WDM and channel multiplexing technologies required for high-capacity THz transmissions. All of these innovations will together allow realizing various forms of adaptive, compact, and high-precision THz photonic systems for different applications such as non-invasive biomedical imaging, secure ultra-fast wireless links, lab-on-chip sensing and diagnostics, environments and industrial monitoring.

Table 6: Summary of Tunability

Technique	Tunability Level	Q-factor Impact	Integration Complexity
Fixed Geometry	None	Stable	Low
Electrostatic Biasing	Moderate	Degrades	High
Geometric Tuning	High	Enhances	Moderate
Thermo-Optic Tuning	Low	Moderate	High

The following table enlists various possibilities to to achieve tunability in filter photonic crystal. It possesses a rigid and well-defined geometry and offers the most stability at the cost of its ruggedness and has a very low tunability of the spectrum. Still, geometrical tuning, explained in the present paper, can provide high tunability with the Q-factor enhancement. It is noted that electrostatic and thermo-optic methods provide an active control but at the same time affect the fabrication processes and can lead to the decrease in the Q-factor.

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