An electrically controlled tunable photonic crystal filter based on thin-film lithium niobate*

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In this paper, we present an electrically controlled tunable narrowband filter based on a thin-film lithium niobate two-dimensional (2D) photonic crystal. The filter incorporates a photonic crystal microcavity structure within the straight waveguide, enabling electronic tuning of the transmitted wavelength through added electrode structures. The optimized microcavity filter design achieves a balance between high transmission rate and quality factor, with a transmission center wavelength of 1 551.6 nm, peak transmission rate of 96.1%, and quality factor of 5 054. Moreover, the filter can shift the central wavelength of the transmission spectrum by applying voltage to the electrodes, with a tuning sensitivity of 13.8 pm/V. The proposed tunable filter adopts a simple-to-fabricate air-hole structure and boasts a compact size (length: 11.57 μm, width: 5.27 μm, area: 60.97 μm^2), making it highly suitable for large-scale integration. These features make the filter promising for broad applications in the fields of photonic integration and optical communication.

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Optical filters are essential instruments for wavelength selection, allowing the isolation of specific wavelengths from a large range while blocking others[1]. It plays an indispensable role in fields such as optical communication and optical sensing[2,3]. In particular, integrated optical waveguide filters have become a research hotspot in recent years due to their small size and ease of large-scale integration[4-6]. In addition, the emergence of photonic crystal waveguides has opened up new possibilities for controlling optical signals and has increased confidence in further development of integrated optics. Through the replacement of material types and the design of different structures, photonic crystals have been harnessed for various applications, including beam splitters[7], electro-optical modulators[8,9], and wavelength-division-multiplexing systems[10].

In recent years, photonic crystal-based optical filters have garnered significant attention among researchers. In 2012, a filter with an X shape was proposed, which utilized triangular lattice photonic crystal silicon rods. This innovative design achieved remarkable transmission rate and quality factor of 100% and 196, respectively, at a wavelength of 1 550 nm[11]. In 2020, HOSSEINZADEH et al[12] designed a novel narrowband optical filter that consisted of seven silicon rods with different radii, forming a resonator. This design resulted in an exceptional quality factor of up to 5 542 at 1 552 nm. Additionally, in 2022, TANG et al[13] designed a filter utilizing Al_2O_3 columns and the unidirectional transport properties and resonant coupling effect of topological photonic states, obtaining an impressive 99.7% transmission rate and a quality factor of 1 560[13]. Most of the photonic crystal-based filters reported in the literature have utilized column structures for device design, often accompanied by complex structural designs to achieve exceptional transmission rate and quality factor. However, the

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existing preparation process poses limitations, as generating two-dimensional (2D) photonic crystals with column structures can be highly intricate and costly. In contrast, air-hole structures offer a simpler and more feasible alternative[14]. Additionally, many of the reported filter devices have large areas exceeding 100 μm^2, which can hinder high integration possibilities due to the increased device area and complex design structures[15]. Therefore, there is an urgent need for the development of photonic crystal filter structures that are easy in fabrication process, with a simple structure and smaller dimensions.

In this paper, we propose an electrically controlled tunable narrowband filter based on a thin-film lithium niobate 2D photonic crystal. The crystal is arranged in a triangular lattice pattern with air holes on the lithium niobate substrate, measuring 11.57 μm in length, 5.27 μm in width, with a device area of 60.97 μm^2. The core components of the filter include a photonic crystal microcavity and a pair of parallel electrodes. The filter has been optimized to achieve a transmission rate of 96.1% at 1 551.6 nm, showing an impressive quality factor of 5 054. Moreover, benefiting from the excellent electro-optic properties of lithium niobate crystals, the designed filter enables electrical control of its transmission wavelength, with a tuning sensitivity of up to 13.8 pm/V. The filter boasts several attractive features, such as a small device size, electro-optical tunability, and an air-hole based structure. These advantages lead to ease of fabrication and a compact form. Consequently, the filter holds promise for applications in photonic integration and optical communications.

The structure of the proposed filter is shown in Fig.1. Its main components comprise a microcavity, two rows of straight waveguides, and two outer parallel electrodes. The filter is constructed with air holes arranged in a triangular lattice on a thin-film lithium niobate substrate, with dimensions of 11.57 μm in length, 5.27 μm in width, and a device area of 60.97 μm^2. Both the microcavity and the straight waveguides are composed of air holes arranged in a triangular lattice pattern on the thin-film lithium niobate. The lattice period between neighboring air holes is denoted as a, the radius of the air holes as r, and the duty cycle as r/a.

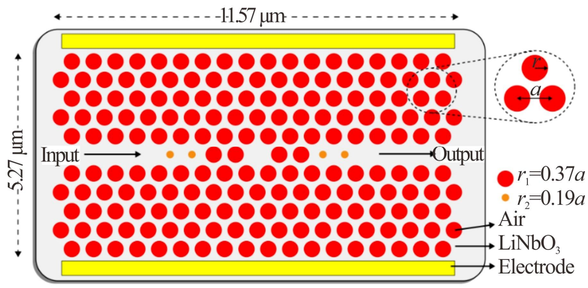

Fig.1 Structure of the electrically controlled tunable filter based on thin-film lithium niobate photonic crystals

A straight waveguide is achieved by removing a column of air holes in a triangular lattice array, resulting in a line defect. The microcavity further divides the waveguide into two symmetrical columns, each with the function of guiding the input and output of light waves, respectively. The microcavity, being the central structure of the filter, functions as a resonant cavity capable of capturing light waves of specific frequencies. This capture depends on factors such as the number of crystal periods between the resonant cavity and the waveguide, the lattice period forming the resonant cavity, and the cavity's geometry.

To design the microcavity, a point defect is first constructed at the middle of the straight waveguide by removing an air hole. Two sets of air holes are then retained on both sides of the point defect to form the resonant cavity. One group consists of two air holes with a radius of r_1=0.37a, primarily serving as the outer wall of the resonant cavity to capture the light. The other group includes two auxiliary holes with a radius of r_2=0.19a, which facilitate the cavity-waveguide coupling of the light to enhance the quality factor of the resonant cavity.

The 2D lithium niobate-based photonic crystal plays a crucial role in the designed filter. We analyzed the photonics band gap of the triangular lattice photonic crystal using the plane wave expansion method and conducted accurate sweep calculations within the range of r/a from 0 to 0.5. This process allowed us to obtain relevant data for all photonics band gaps at various duty cycles. In our calculations, the center frequency is set at 1 550 nm, the background dielectric material is lithium niobate (n_L=2.212 85), and the surrounding medium is air (n_a=1). The results of these calculations are illustrated in Fig.2.

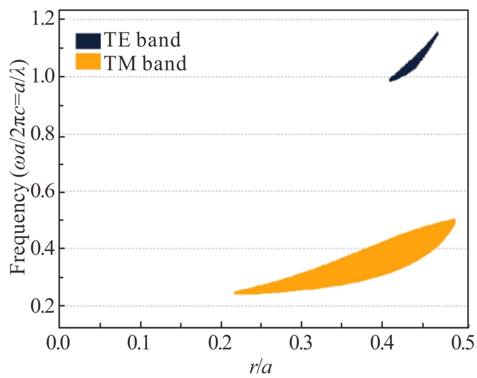

Fig.2 Band gap map of a 2D photonic crystal of lithium niobate with triangular lattice

Based on the sweep results, we observe that the air-hole structure generates two band gaps. One is the narrower transverse electric (TE) mode band gap, which starts to appear at r/a=0.406. The other is the transverse magnetic (TM) mode band gap, displaying an excellent bandwidth, and it emerges at r/a=0.213, gradually widening with increasing duty cycle. Out of these two band gaps, the TM mode band gap stands out with its exceptional bandwidth and low normalized frequency. Moreover, almost half of the band gap lies within the duty cycle interval of 0.2—0.4, favoring the stability of the photonic crystal. On the other hand, the TE mode band gap has smaller bandwidth and appears at higher duty cycle. Its band gap center is also situated at a higher position of the normalized frequency, leading to an enhancement of the lattice period and reduced device integration. Given these considerations, the TM mode band gap is chosen as the optimal candidate for constructing the photonic crystals.

Within the duty cycle interval of 0.2—0.4, both the bandwidth and the central frequency of the TM mode's band gap increase as the r/a rises. However, it is important to consider the stability of the structure, which may decrease when the duty cycle becomes excessively large. Therefore, we identify the optimal r/a range to be 0.35—0.4, and ultimately choose a representative value of r/a=0.37. With r/a=0.37, the band gap structure of the triangular lattice is depicted in Fig.3. To position the center frequency of the resonant cavity close to 1 550 nm, we set a=609 nm. Consequently, the band gap width of the TM mode is from 1 355 nm to 1 691 nm, providing ample wavelength range redundancy for capturing light within the 1 550 nm band.

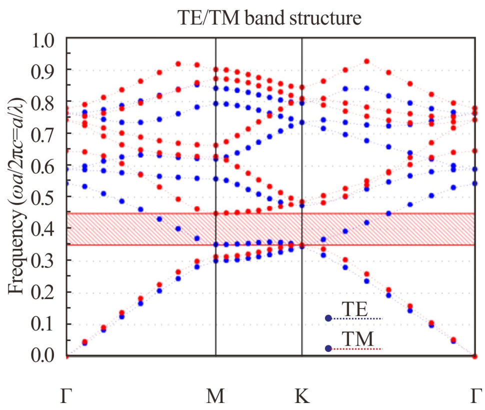

Fig.3 Photonic band gap structure at *r/a*=0.37

As an outstanding electro-optic material, lithium niobate offers extensive application prospects in the field of optoelectronic communication. The core principle underlying the electro-optical effect is the Pockels effect, wherein the arrangement of electrons within the crystal undergoes changes in response to an external electric field. These changes are then manifested as macroscopic alterations in the refractive index[16,17]. In a 2D plane, the refractive index variation caused by the Pockels effect can be expressed as follows

$$\Delta n_{\mathrm{L}} = -\frac{1}{2} n_{\mathrm{L}}^{3} r_{33} \frac{V}{d}, \tag{1}$$

where n_{L} represents the refractive index of lithium niobate, r_{33} is its electro-optical coefficient, V is the voltage applied to the electrodes, and d denotes the distance between the electrodes. Since the center wavelength of the filter is 1 551.6 nm, the corresponding refractive index of lithium niobate is n_{L}=2.212 85. From Fig.1, it is observed that the distance between the electrodes is d=6.8 μm.

By applying the above principle and keeping the other parameters unchanged, the designed electrically controlled tunable microcavity filter can effectively change the refractive index. As a result, it can achieve the movement of the central wavelength through the electrodes placed on both sides of the resonant cavity.

Generally, when evaluating the performance of a filter, the quality factor is defined as the ratio of the wavelength at the center of the transmission spectrum to the full width at half maxima (*FWHM*).

$$Q = \frac{\lambda_0}{\Delta\lambda}, \tag{2}$$

where Q is the quality factor, λ_0 is the transmission center wavelength, and $\Delta\lambda$ is the *FWHM*.

In other words, the quality factor is a key parameter in filter design, and a smaller *FWHM* value indicates a higher quality factor and better wavelength selectivity. Conversely, a larger *FWHM* value suggests a lower quality factor and poorer wavelength selectivity. It's important to note that as the *FWHM* decreases, the filter loss may increases[2]. Therefore, in most cases, it's challenging to achieve perfect transmission rate and a very high quality factor simultaneously. Good filters need to strike a balance between high transmission rate and high quality factor to achieve optimal performance.

The remarkable wavelength selectivity of the filter within the 1 550 nm band is attributed to the presence of the auxiliary holes on the outside of the main part of the resonant cavity. This structure effectively filters out unwanted light, allowing only the center wavelength to pass through. To validate the impact of the auxiliary holes on the filter's performance, we calculated the quality factor and transmission rate of the microcavity filter for various r_2, while keeping the center wavelength fixed at 1 551.6 nm. The calculations were performed with a step size of Δr_2=0.1a.

In Fig.4, we observe the change in transmission rate and quality factor of the filter as the r_2 varies at the center wavelength of 1 551.6 nm. When there is no auxiliary holes (r_2=0), the filter exhibits a high transmittance of 99.1%, almost lossless. However, the quality factor is significantly low at only 1 004. As the radius of the auxiliary holes increases, there is a gradual decrease in the transmission rate of the filter, while the quality factor shows a continuous increase. At r_2=0.2a=121.8 nm, the transmission rate of the filter starts to drop rapidly to 90.4%, further declining to 59.5% at r_2=0.21a=127.9 nm. Though the quality factor experiences a sharp increase during this process, reaching up to 10 000, the substantial loss of transmission rate is deemed unacceptable. Therefore, the optimal value of the radius of the auxiliary aperture should be chosen before the rapid decrease in transmittance, i.e., r_2=0.19a=115.7 nm.

The transmission spectrum of the optimized microcavity filter is illustrated in Fig.5. From the graph, it can be inferred that the filter exhibits a peak transmission rate of 96.1%, an *FWHM* of 0.307 nm. Substituting the above data into Eq.(2) gives a quality factor of 5 054. At this point, the proposed filter strikes a balance between transmission rate and a high quality factor.

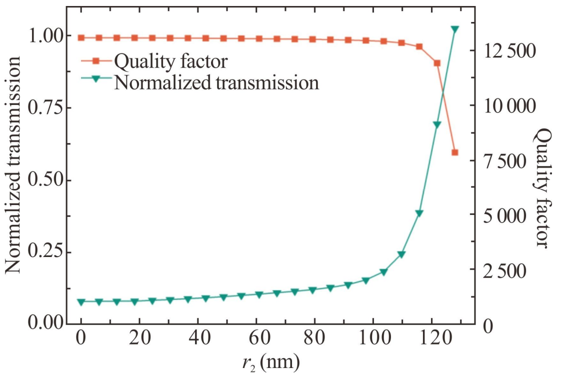

Fig.4 Normalized transmission and quality factor of the microcavity filter with different auxiliary hole radii r_2

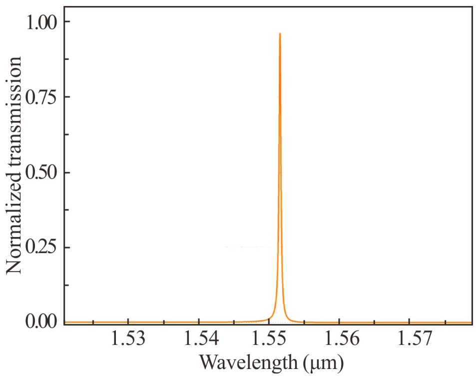

Fig.5 Transmission spectrum of the proposed optimized microcavity filter at 1 551.6 nm

By using the electro-optical properties of lithium niobate crystals, the tunable feature of the transmitted wavelength is achieved through the adjustment of the voltage applied to the filter electrodes. Once the optimal transmittance and quality factor of the proposed filter are determined, we proceed to investigate the variations in the transmission spectrum under different voltage loads. Fig.6 displays the transmission spectrum of the filter at various voltages, while Fig.7 illustrates the correlation between the center wavelength of the transmission spectrum and the applied voltage. Additionally, Tab.1 provides an overview of the relationships between the filter's transmission wavelength, transmission rate, quality factor, and the corresponding voltages.

As depicted in Fig.6 and summarized in Tab.1, the center wavelength of the filter can be tuned by adjusting the voltage across the electrodes. Increasing the applied voltage results in a change in the refractive index of lithium niobate, leading to a deviation in the transmission spectrum compared to when no voltage is applied. During the gradual movement of the center wavelength in the transmission spectrum, the transmission rate and quality factor of the filter show minimal variations, consistently hovering around 96% and 5 000, respectively.

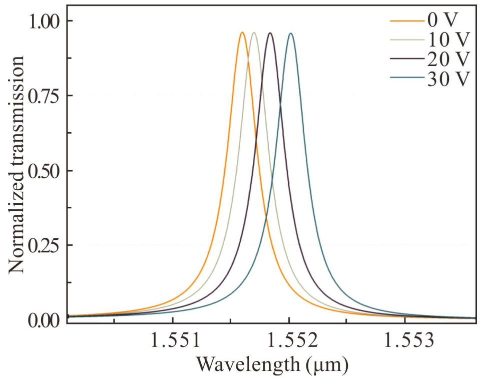

Fig.6 Transmission spectra of microcavity filters at different voltages

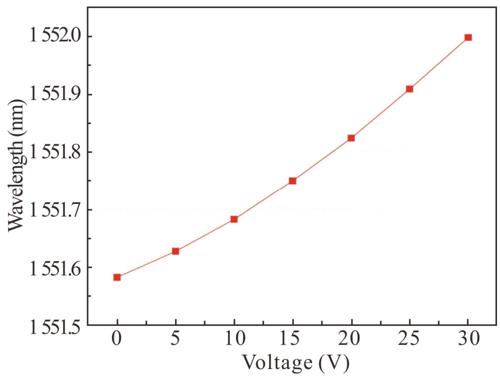

Fig.7 Relationship between transmission spectrum center wavelength and loading voltage

Tab.1 Center wavelength, transmission rate and quality factor of filter transmission spectrum at different voltages

Voltage (V)	Center wave-length (nm)	Transmission rate (%)	Quality factor
0	1 551.58	96.1	5 054
10	1 551.68	96.0	5 054
20	1 551.82	95.8	4 989
30	1 552.00	95.7	4 990

Furthermore, as shown in Fig.7, the shift in the center wavelength of the transmission spectrum exhibits a nearly linear correspondence with the applied voltage. The tuning sensitivity of the proposed filter is determined to be 13.8 pm/V.

Tab.2 presents a comparison between our designed filters and the related works in recent years. In comparison to them, we have achieved a balance between transmittance and quality factor, and our devices have smaller dimensions, making them more conducive to large-scale integration. Furthermore, our filters are based on lithium niobate crystals, enabling electrical control of the transmission wavelength.

Tab.2 Comparison between related studies and our designed filter

Reference	Device area (μm^2)	Transmission rate (%)	Quality factor
[4]	248.4	90	NA
[5]	323	97	444
[6]	130	100	103
[11]	NA	100	196
[12]	116.6	100	5 542
[13]	NA	99.7	1 560
Our work	60.97	96.1	5 054

In this paper, we propose a tunable narrowband filter based on a lithium niobate 2D photonic crystal. The lithium niobate photonic crystal is characterized by a period constant of a=609 nm and a duty cycle of r/a=0.37. The key components of the filter include a microcavity, two rows of straight waveguides, and two outer parallel electrodes. Due to the existence of auxiliary holes (r_2=0.19, a=115.7 nm) outside the microcavity, the microcavity filter achieves a balance between transmission rate and high quality factor. It attains a peak transmission rate of 96.1% at 1 551.6 nm, an *FWHM* of 0.307 nm, and a quality factor of 5 054. Additionally, the filter exploits the excellent electro-optical effect of the lithium niobate material, allowing it to be tuned to the center wavelength of the transmission spectrum through voltage loading on the electrode, with a tuning sensitivity of 13.8 pm/V.

In conclusion, the tunable narrowband filter proposed in this paper is based on a lithium niobate photonic crystal with an air-hole structure, making it more engineering feasible and compact in size. Its ability to change the center wavelength of the transmission spectrum through the electro-optic effect adds to its versatility. These advantageous features render the designed filter highly attractive for applications in photonic integration and optical communication.

Ethics declarations

Conflicts of interest

LIN Wei is an editorial board member for Optoelectronics Letters and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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