Postprint: Study of a K-band Dual-Mode Ring Filter for the Tianma Telescope

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Abstract

A low-insertion-loss, steep-skirt dual-mode bent square-ring bandpass filter with stubs for miniaturized integrated downconversion systems in radio astronomy K-band (18-26.5 GHz) multi-beam receivers. The filter utilizes orthogonal direct-feed lines to achieve low insertion loss, and the addition of tuning stubs creates a broadband filter with steep skirts. Measurement results indicate: the single-ring filter exhibits a 3dB bandwidth of 42.8%, return loss below -20dB in the 17.4-26.9 GHz band, and insertion loss of -1.05dB. Stopband rejection exceeds 35dB in the 15.1-16 GHz and 28.1-28.9 GHz bands; the dual-ring filter demonstrates a 3dB bandwidth of 39.8%, return loss below -14dB in the 17.7-26.5 GHz band, and insertion loss of -1.27dB. Stopband rejection exceeds 35dB in the 12.8-15.3 GHz and 27.9-30.6 GHz bands. The measured and simulated results for both filters show excellent agreement.

Full Text

Study of K-Band Dual-Mode Ring Filters for the Tianma Telescope

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Abstract

This paper presents a low insertion-loss, sharp-rejection, wide-band dual-mode microstrip bandpass filter using a meander square loop with two tuning stubs, designed for miniaturized integrated down-converter systems in K-band (18–26.5 GHz) multi-beam receivers for radio astronomy. The filter employs orthogonal direct-connected feed lines to achieve low insertion loss, and loading tuning stubs creates a broadband filter with steep band edges. Measured results demonstrate that the single-ring filter achieves a 3 dB bandwidth of 42.8%, with return loss better than -20 dB from 17.4 GHz to 26.9 GHz, and insertion loss of -1.05 dB. The stopband rejection exceeds 35 dB in the ranges of 15.1–16 GHz and 28.1–28.9 GHz. The dual-ring filter achieves a 3 dB bandwidth of 39.8%, with return loss better than -14 dB from 17.7 GHz to 26.5 GHz, and insertion loss of -1.27 dB. The stopband rejection exceeds 35 dB in the ranges of 12.8–15.3 GHz and 27.9–30.6 GHz. The measured results for both filters show excellent agreement with simulation results.

Keywords: multi-beam; Tianma telescope; dual-mode; bandpass filter

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The K-band (18–26.5 GHz) is a crucial observational window in radio astronomy for studying star formation, particularly massive star formation. Several ammonia molecular lines are considered powerful tools for determining physical conditions such as density and temperature in dense molecular cloud cores within star-forming regions, while the 22 GHz water maser is typically associated with these regions. This band also contains methanol maser lines at approximately 20.0 GHz, 23.1 GHz, and 25.0 GHz, which are commonly associated with massive star-forming regions, making the search for such masers an important research topic [1]. Multi-beam receiver systems can significantly enhance the survey efficiency of radio telescopes, and minimal beam spacing ensures aperture efficiency and pattern symmetry for edge beams, but this also imposes stringent requirements on the miniaturization of receiver channels. The Shanghai 65-meter Tianma Telescope is currently developing a K-band seven-beam receiver with a physical beam spacing of only 110 mm, necessitating the use of Microwave Integrated Circuit (MIC) technology for the down-converter system. This paper investigates an 18–26.5 GHz microstrip broadband filter structure for application as the first-stage RF filtering in the integrated down-converter system of the K-band receiver, achieving image rejection of RF signals and suppressing local oscillator leakage from the mixer to the link system.

[Figure 1: see original paper]

Fig. 1 shows the system architecture of the K-band dual-beam receiver, which has been deployed on the Tianma Telescope. The K-band microstrip filter studied in this paper is intended for the down-converter system of the K-band seven-beam receiver. The down-converter system of the K-band dual-beam receiver uses discrete component assembly with a relatively large structure. To achieve a compact down-converter system, MIC technology is being adopted for the design of the down-converter system for the K-band seven-beam receiver.

Common broadband filter topologies include stub-loaded multi-mode ring filters, Stepped-Impedance Resonator (SIR) multi-mode filters, and other types of multi-mode filters [2]. Stub-loaded multi-mode ring filters exhibit steep band-edge characteristics, while SIR-based multi-mode filters suffer from gradual stopband attenuation. Since the design requirement is for a broadband filter with steep band-edge characteristics, this paper employs a stub-loaded dual-mode meander square loop filter.

A broadband filter formed by loading short-circuited stubs on a bandstop structure using a square ring resonator with direct-connected feed lines eliminates coupling gaps, thereby overcoming the drawback of high insertion loss [3].

Since the filter designed in this paper must be integrated into the K-band downconverter system, GSG pads are designed at the filter input and output for wire bonding to facilitate integration.

1 Dual-Mode Meander Square Loop Bandpass Filter with Stubs [4]

The dual-mode bandstop filter using a meander ring resonator with direct-connected orthogonal feed lines is shown in Fig. 2. This structure has no coupling gaps, with the meander ring resonator directly connected to the feed lines. The perimeter of the meander ring resonator is calculated as follows:

$$L = n \cdot \frac{\lambda_g}{2}$$

where n is the mode number and λ_g is the guided wavelength. This meander loop operates as a dual-mode bandstop filter. Taking $n = 2$, we obtain:

$$L = \lambda_g$$

The filter can be divided into two symmetrical structures along the dashed line shown in Fig. 2 [Figure 2: see original paper], enabling analysis using odd-even mode theory. The equivalent circuits for odd and even mode analysis are shown in Fig. 3 [Figure 3: see original paper]. The characteristic impedance of the square loop is Z_1, while the input and output characteristic impedance is Z_0.

[Figure 2: see original paper]

[Figure 3: see original paper]

Loading a pair of open-circuited tuning stubs onto the dual-mode bandstop filter with direct-connected orthogonal feed lines yields a broadband bandpass filter, as shown in Fig. 4 [Figure 4: see original paper]. The open-circuit tuning stubs have characteristic impedance Z_2 and length $\lambda_g/4$. According to the theory of stub-loaded square loop filters, the center frequency depends on both the loop perimeter and the length of the loaded stubs, while the transmission zeros are determined by the impedance ratio:

$$a = \frac{Z_1}{Z_2}$$

When the center frequency f_0 is determined, the desired filter bandwidth can be obtained by adjusting the impedance ratio $a = Z_1/Z_2$. For a values ranging from 0.5 to 3.3, the filter bandwidth varies from 32% to 55% [5].

[Figure 4: see original paper]

2 Filter Design

This paper designs a bandpass filter with 18-26.5 GHz bandwidth. The substrate has a relative permittivity of 2.2 and thickness of 0.254 mm. The design begins with the dual-mode meander square loop bandstop filter. For convenience, we take $Z_1 = 50\,\Omega$ and $Z_0 = 50\,\Omega$. According to equation (2), we calculate $L = 6.76$ mm. Initial simulation reveals the center frequency f_0 deviates slightly from 22.25 GHz, and optimization yields $L_1 = L_2 = 1.81$ mm.

[Figure 5: see original paper]

The center frequency depends not only on the loop perimeter but also on the length of the loaded stubs. Here, open-circuit tuning stubs with length $\lambda_g/4$ are loaded [6]. Simulation and optimization produce $Z_2 = 55\,\Omega$. This paper designs a filter for 18-26.5 GHz with center frequency at 22.25 GHz. Simulation and optimization yield $a = 0.9$.

Simulations were performed for $a = 0.7, 0.9, 1.1$, with results shown in Fig. 6 [Figure 6: see original paper]. Final optimization with $a = 0.9$ yields a filter with 1 dB bandwidth of 18-26.5 GHz, as shown in Fig. 7 [Figure 7: see original paper].

[Figure 6: see original paper]

[Figure 7: see original paper]

Since this filter is intended for RF integrated down-converter systems, coplanar waveguide structures are designed at the input and output ports for wire bonding. The fabricated filter is shown in Fig. 8 [Figure 8: see original paper], with simulation and measurement results shown in Fig. 9 [Figure 9: see original paper].

[Figure 8: see original paper]

[Figure 9: see original paper]

Fig. 9 shows excellent agreement between measured and simulated results. The measured center frequency is 22.15 GHz with a 3 dB bandwidth of 42.8%. The return loss is better than -20 dB from 17.4 GHz to 26.9 GHz, with insertion loss of -1.05 dB. The stopband rejection exceeds 35 dB in the ranges of 15.1-16 GHz and 28.1-28.9 GHz.

The single-ring resonator filter exhibits relatively gradual band edges and moderate out-of-band suppression. To achieve stronger out-of-band suppression, an additional square loop resonator is added, as shown in Fig. 10 [Figure 10: see original paper], with the fabricated device shown in Fig. 11 [Figure 11: see original paper].

The two resonators are cascaded using a microstrip line of length $\lambda_g/4$. Final simulation optimization determines the cascaded microstrip line length as $L_c =$ 9.1 mm. Simulation and measurement results are shown in Fig. 12 [Figure 12: see original paper].

[Figure 10: see original paper]

[Figure 11: see original paper]

[Figure 12: see original paper]

Fig. 12 demonstrates excellent agreement between measured and simulated results. The measured center frequency is 22.1 GHz with a 3 dB bandwidth of 39.8%. The return loss is better than -14 dB from 17.7 GHz to 26.5 GHz, with insertion loss of -1.27 dB. The stopband rejection exceeds 35 dB in the ranges of 12.8–15.3 GHz and 27.9–30.6 GHz.

This paper designs a bandpass filter by loading a pair of open-circuit tuning stubs onto a dual-mode meander square loop bandstop filter with direct-connected orthogonal feed lines. Both single-ring and dual-ring resonator filters are implemented, with 50 Ω feed lines directly connected to the meander square loop resonator and short-circuited stubs loaded at the diagonal positions of the input and output to achieve a broadband filter. Simulation and measurement results show that both filters meet design requirements. The dual-ring resonator filter provides superior out-of-band suppression and steeper band edges compared to the single-ring version, albeit with slightly worse insertion loss and return loss performance.

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Note: Figure translations are in progress. See original paper for figures.