Novel compact waveguide filtering twist for computer numerical control machining

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In this letter, the authors present a novel compact waveguide filtering twist that can be readily fabricated from metal using the computer numerical control (CNC) machining process. This filtering twist comprises four coupled resonators that are rotationally deformed to provide the desired 90° twist. Such resonator structures eliminate the use of curved features and therefore are ideally suitable for conventional CNC machining. The proposed design offers appealing advantages, including great compactness, easy fabrication, and good scalability to millimetre-wave and terahertz frequencies. The design is demonstrated at X-band and has a fourth-order Chebyshev filter response (bandwidth 0.4 GHz, centred at 10 GHz). The good agreement between simulation and measurement results validates the proposed concept.

Introduction: Waveguide components have been widely utilised for applications such as satellites, communications, and radars, due to their attractive advantages in terms of high power-handling capability and small transmission loss. Waveguide twists are usually employed to connect two devices or subsystems with rotating misaligned ports, and this type of waveguide component has been explored actively (e.g., [1–6]). The typical twists (commercially available) usually adopt a helicoidal rotation along their longitudinal axis. This is not ideal for highly integrated and compact systems because several wavelength lengths are required to achieve low return loss (RL) [1]. Alternative designs with great performance based on novel waveguide sections have been reported in [2–6], and they are generally broadband and relatively compact.

Miniaturization and low loss are of great importance to the design of waveguide components and subsystems. In addition to pursuing a reduced size for individual devices, an alternative approach is integrating two or more functionalities into stand-alone devices [7, 8]. Twists with integrated filtering functionality were proposed in [9–12]. In [9], a single-waveguide device including three RF functionalities, that is, lowpass filtering, bending, and twisting, was described. Following this integrated architecture, a 3-D printed waveguide twist with bandpass filtering response was reported in [10, 11]. Polarization rotation was achieved by gradually rotating coupled resonators. Moreover, a 3-D printed smooth twist that utilizes a metal-insert filter technique has recently been reported in [12]. All these designs are in helicoidal or tilting geometries, which can be readily produced using 3-D printing but are difficult or impossible to fabricate using conventional computer numerical control (CNC) machining. Despite the fact that 3-D printing enables easy fabrication of complex waveguide features (e.g., [13, 14]), there exist applications or scenarios where CNC machined components are still preferred such as those involving high power/temperature or requiring decent durability.

This letter presents a novel compact filtering twist, as shown in Figure 1, which can be easily fabricated using CNC machining. By utilising the rotational deformed resonators, convoluted geometries or undercuts can be avoided. The proposed structure was designed to have a fourth-order Chebyshev bandpass filtering response and perform a 90° polarization rotation. The X-band prototype was fabricated from aluminium alloy using CNC machining and split block technology. The design could be readily scaled to higher frequencies and manufactured using a high-precision CNC machining process.

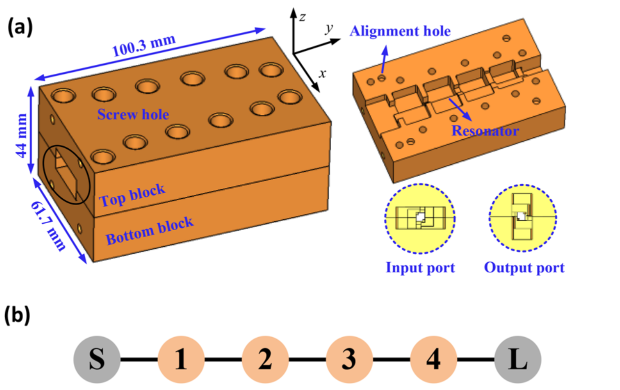

Fig. 1 *(a) Prototype construction of the fourth-order filtering twist. The left image depicts the assembled prototype and the right images show the machined half blocks and a close-up view of the input and output ports. (b) Coupling topology of the proposed filtering twist*

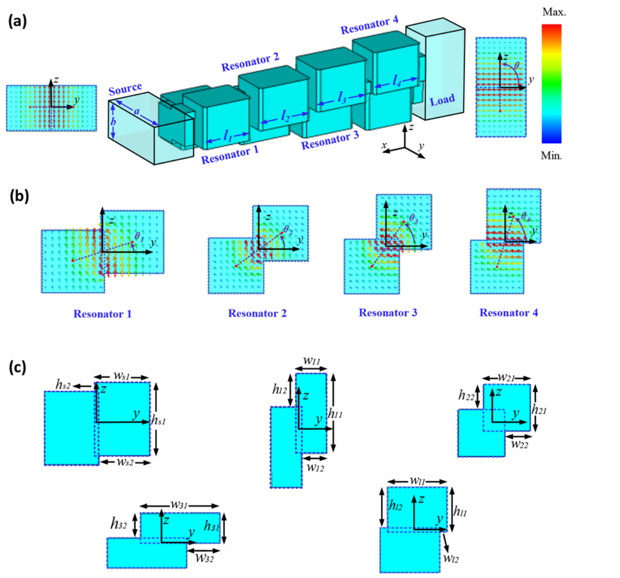

Fig. 2 *(a) Illustration of the filtering twist, showing its internal structure with critical internal dimensions. (b) Progressive changes in resonators' cross-sections and their corresponding electric field distributions. (c) Cross sections of the coupling irises*

Filtering twist design: An X-band (8–12 GHz) version of the filtering twist has been designed, manufactured, and characterized. The filter is specified as a fourth-order Chebyshev bandpass response with a centre frequency of 10 GHz, a bandwidth of 0.4 GHz (fractional bandwidth of 4%), and a passband RL of 20 dB. Figure 1b shows the filtering twist schematically, with the grey circles denoting the source and load and the yellow circles representing the resonators. Solid lines stand for the coupling between resonators. The un-normalized coupling coefficients between resonators are $M_{12} = M_{45} = 0.036$, $M_{23} = M_{34} = 0.028$ and the external quality factor of the first (Q_{es}) and the last (Q_{el}) resonators are calculated to be $Q_{es} = Q_{el} = 23.326$ [15]. The physical dimensions corresponding to the coupling coefficients and external quality factor were obtained by following the standard technique described in [15].

Figure 2a shows the internal structures of the filtering twist. This structure consists of input/output waveguides, resonators, and irises. The input/output waveguides with a standard WR-90 waveguide cross-section (22.86 mm × 10.16 mm) are polarized orthogonally. Both WR-90 waveguides have been extended by 12 mm to accommodate standard waveguide flanges and screws. The resonator was constructed by superposing two identical square (dimensions 11.43 mm × 11.43 mm). To rotate the polarization of the desired resonant mode, this pair of sub-rectangles rotate on the centre of the cross-section of input and output waveguides (i.e., the origin of coordinates in Figure 2b). As shown in Figure 2b, the centre of the square moves from the y-axis to the z-axis through a series of progressive rotations. The proposed filtering twist

Table 1. *Detailed dimensions of the filtering twist (unit: mm)*

Parameter	Value	Parameter	Value	Parameter	Value
a	22.86	h_{s2}	1.13	w_{31}	8.12
b	10.16	w_{11}	2.35	h_{31}	2.30
l_1	14.83	h_{11}	8.12	w_{32}	3.41
l_2	15.82	w_{12}	1.79	h_{32}	1.74
l_3	15.86	h_{12}	3.41	w_{l1}	9.03
l_4	14.82	w_{21}	4.44	h_{l1}	6.38
w_{s1}	6.33	h_{21}	4.44	w_{l2}	1.13
h_{s1}	9.03	w_{22}	2.25	h_{l2}	5.82
w_{s2}	5.77	h_{22}	2.25		

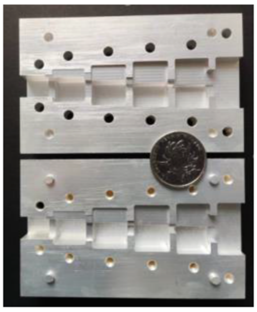

Fig. 3 *Photograph of the fabricated filtering twist*

can be considered a combination of these resonators, each with a rotation angle to achieve the desired total rotation between the input and output waveguides. If the total rotation angle between the input/output waveguide is Φ, the rotational offset angle of each resonator is $\Phi/(N + 1)$, where N is the order of filtering crossover. Here, the calculated rotation angle $\Delta\theta$ between adjacent resonators or waveguides is 18°. So, the rotation angles labelled in Figure 2a are $\theta_1 = 18°$, $\theta_2 = 36°$, $\theta_3 = 54°$, and $\theta_4 = 72°$. The corresponding electric fields in different resonators are shown in Figure 2b. It can be observed that the dominant mode TE_{101} slowly rotates along the filtering twist to convert to TE_{011} mode. As a result, a transition from the horizontal port to the vertical port has been produced. Similar to the conventional waveguide bandpass filter, the resonant frequency was determined by the length of the resonant cavity, and irises were used to control the coupling strength. Considering the irregular geometry of the resonator and different polarization directions in adjacent resonators, the geometries of irises were specifically designed. The cross-sections of the irises are shown in Figure 2c with the critical dimensions indicated. The inner corners of each resonant cavity were rounded with a radius of 0.8 mm to cope with CNC machining. Resonant frequency shift due to the rounded corners was eliminated by performing further optimization, and that is why the final dimensions of the resonators and irises are asymmetrical. Table 1 gives all the critical dimensions after optimisation.

Fabrication and measurements: The filtering twist structure has been fabricated from aluminium alloy using conventional end-mill machining and silver plated. Four 3-mm-diameter dowel pins have been used to align the split blocks. Figure 3 shows the CNC-machined filtering twist pieces and the assembled device. The top and bottom blocks were designed to be identical to reduce manufacturing costs. The prototype block has H-plane split waveguides on the left side and E-plane split waveguides on the right side. After the machining process, both pieces were aligned using four alignment pins and tightened by six screws on each side. The fabricated block has a volume of $100.3 \times 61.7 \times 44$ mm^3.

The S-parameter measurements were performed using a Keysight E8363B vector network analyzer (VNA) subject to a Thru-Reflect-Line (TRL) calibration. Figure 4 plots the measured results of the filtering twist in comparison with the simulations where the measured results are denoted with solid lines and simulated ones with dashed lines. The simulation was carried out using a perfectly smooth aluminium alloy (i.e., a

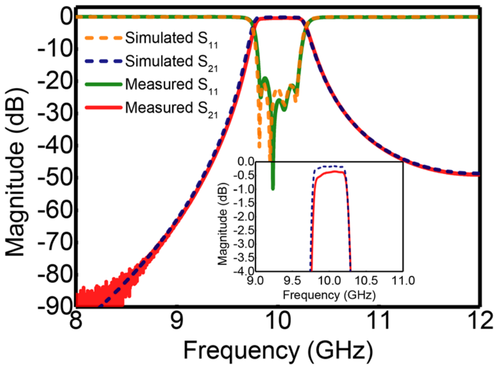

Fig. 4 *Simulated and measured results of the manufactured filtering twist. The inset is the expanded view of passband insertion loss*

Table 2. *Comparison with the state-of-the-art filtering twist*

Ref.	f_0 (GHz)	FBW (%)	RL (dB)	Δf (%)	Tech.
[10]	32	3.125	15	0.32	3D printing
[11]	34	2.9	> 15	0.36	3D printing
[12]	10.8	3.7	18	N/A	3D printing
T.W.	10	4	19	0.09	CNC

N/A, not available; Ref., reference; Tech.: technology; T.W., this work.

conductivity of 2.61×10^7 S/m). It can be observed that the measured centre frequency is shifted (Δf) downwards by ~9 MHz and the measured bandwidth is ~18 MHz narrower than the prediction. The negligible frequency shift and bandwidth deviation are believed to be mainly caused by manufacturing tolerance. The measured RL is better than 19 dB across the passband. It is believed that the higher-than-expected RL is attributed to the small misalignment between two pieces of the device. The expanded view of the S_{21} provided in the inset of Figure 4 shows an average insertion loss of ~0.43 dB across the passband for the measurement, while the simulated one is ~0.22 dB. The difference in insertion loss may be attributed to possible imperfect contacts between two pieces, which results in energy leakage. This could be improved by having a better surface finish and/or using more screws when joining two pieces in assembly. Table 2 presents a comparison of this CNC-based work with other 3-D printed filtering twists. This filtering twist exhibits excellent performance in terms of frequency shift and RL, in addition to its appealing characteristics of high power/temperature and excellent durability.

Conclusion: This letter reports on a novel X-band waveguide twist with an integrated fourth-order Chebyshev filter. The filtering twist structure proposed in this letter is ideally suitable for the CNC machining process as it avoids curved features and is therefore easy for fabrication. The prototype device has shown a good agreement between the measured and simulated results. The proposed design can be readily scaled to higher frequencies and therefore may find useful applications in millimetre-wave subsystems.

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