40 GHz compact TFMS meander-line bandpass filter on silicon substrate


Presented is a compact millimetre-wave bandpass filter using a thin-film microstrip meander line on standard 0.18 µm CMOS silicon substrate without any post-processing step yet still reducing the substrate loss and crosstalk to a large extent. To miniaturise overall circuit size, a half-wavelength resonator is constructed in meander-line configuration and its resonant frequency is designed to be 40 GHz. The prototype single-resonator bandpass filter occupies a circuit area of 210 × 210 µm on silicon. Measured insertion loss is 2.5 dB, which agrees well with the design value in the simulations.

Introduction: With recent advances in CMOS technology, achievable frequencies of operation, particularly of RF and analogue circuits, have increased rapidly. This allows CMOS technology to be explored for use in a variety of millimetre-wave applications such as wireless LAN, automotive radar, and the SONET system [1]. With this in view, high-quality passive components on silicon have been the focus of research since the early foray of silicon technology in the RF domain.

To circumvent the issue of high dielectric loss in standard low-resistivity (10 Ω cm) silicon substrate, various approaches have been proposed which include ion-implantation [2], the micromachining technique [3], and a thick isolated interface layer [4]. However, standard CMOS technology, without any post-processing, is always preferred owing to its maturity as well as its low cost. Further, thin-film microstrip (TFMS) [5] implementations have been demonstrated with several promising transmission characteristics over a wide frequency range (1–110 GHz). Interestingly, TFMS circuits can be easily realised in a standard CMOS process without any post-processing step. The undesired coupling between the low-resistivity silicon substrate and constituted circuits can be very effectively reduced using a grounded metal layer [5]. In this Letter, a millimetre-wave bandpass filter with reduced insertion loss is proposed, designed and fabricated using TFMS meander lines in a standard 0.18 µm CMOS process. Using a grounded metal layer, the designed filter shows a good passband at 40 GHz with low transmission loss and highly miniaturised size. Measured results are in good agreement with those simulated by SONNET EM Suite [6] up to 110 GHz.

TFMS meander-line resonator filter: Fig. 1 shows a schematic of the proposed 40 GHz bandpass filter in standard 0.18 µm CMOS process technology with six metal (aluminium) level interconnects. We designed a single-layer TFMS meander line to make up a compact resonator with a resonant frequency of 40 GHz. The straight length of such a meander-line resonator is about one half-wavelength (λ/2) on silicon. We chose both the strip and the slot widths to be equal to 10 µm, while the length of the broadside coupling arms (Lc), located in the next lower metal layer, is set to 210 µm.

The design process started with the investigation of the quality- or Q-factor of such a resonator formed on different metal layers. As is well known, the unloaded Q factor (QL) can be explicitly derived from S-parameters by modelling or testing this meander-line resonator under the weak coupling case, i.e. short coupling length (LC) shown in Fig. 1:

\[ Q_L = \frac{f_0}{\Delta f} \times (1 - |S_{11}|) \]  

where \( f_0 \) is the fundamental resonant frequency and \( \Delta f \) is the 3 dB absolute bandwidth. Under weak coupling excitation, the magnitude of the transmission coefficient \( |S_{11}| \) is very small and approaches zero with the high substrate loss. As a result, (1) can be further simplified, with the unloaded \( Q_L \) and loaded \( Q_u \) quality factors being almost the same:

\[ Q_u \approx Q_L = \frac{f_0}{\Delta f} \text{(weak coupling)} \]  

Typically, to achieve a higher \( Q_u \) with a thicker silicon-oxide layer [7], the top metal (M6) with thickness of about 2 µm is used for the signal line and the bottom layer (M1) with thickness of about 0.5 µm is used for the ground plane. As shown in Fig. 2, the unloaded quality factor of the meander-line resonator, placed at different metal layers, can be directly obtained based on (2). As the resonator is located from M2, M3, M4, M5 to M6, \( Q_u \) is found to increase, being 1.8, 3.9, 5.9, 7.8 to 19.5 for M2, M3, M4, M5 to M6, respectively. It can be easily understood that |\( S_{11} |\) gets a gradual increment with a sharpened peak if the resonator is placed in the upper interconnect layers.

Fig. 2 Simulated frequency responses of proposed meander-line resonator in different metal levels under weak coupling excitation (LC = 0 µm)

Fig. 3 Impact of ground shield on simulated frequency responses of proposed 40 GHz bandpass filter

Fig. 3 shows the simulated S-magnitudes of the designed single-stage bandpass filter with and without a ground shield at M1. For the filter with the ground shield, excellent passband response is achieved with only 2.0 dB insertion loss around 40 GHz. Furthermore, the first spurious passband at twice the fundamental resonant frequency of 40 GHz is fully suppressed. It can be intuitively interpreted that this harmonic suppression is realised by the coupling zero between the distributed coupled feed line and the meander line. In contrast, the filter without
the ground shield shows poor filtering performance with much lower rejection in the upper stopband above 40 GHz, as can be seen from the dashed curves in Fig. 3.

Experimental verification: The inset of Fig. 4 illustrates the top-view photograph of the fabricated bandpass filter. The overall circuit is only $210 \times 210 \, \mu m$ in area or $\lambda/20$ length of a side. Fig. 4 illustrates the simulated and measured frequency responses of the transmission and reflection coefficients, $|S_{21}|$ and $|S_{11}|$, of this bandpass filter with the resonator installed in M6. Over a wide frequency range from 1.0 to 110.0 GHz, the predicted and measured results are seen to be in good agreement. Measured results show minimum insertion loss in the passband to be 2.5 dB at 41.5 GHz, while return loss is higher than 15 dB. In addition, spurious suppression reaches 36 dB around 100 GHz. The predicted low loss and good filtering performance, described in the preceding Section, have been successfully verified by the experimentally measured results.

Fig. 4 Comparison of measured (dotted) and simulated (line) insertion loss and return loss for 40 GHz bandpass filters
Inset: Photo-micrograph of fabricated 40 GHz TFMS meander-line bandpass filter

Conclusions: A compact and low-loss 40 GHz bandpass filter using a TFMS meander line is proposed, designed and fabricated in a standard 0.18 $\mu m$ CMOS technology, without any post-processing steps. The compact size of the filter is achieved with the help of a meander-line resonator while losses are minimised by placing a ground plane at the bottom layer in a six-metal level CMOS process. A good millimetre-wave passband with low insertion loss predicted by the design simulations has been experimentally verified. This work has demonstrated the potential of realising a variety of advanced millimetre-wave filter blocks using low-cost, mature and high-reliability standard CMOS silicon technology.