Reflection mode mm-wave on-chip notch filters using coupled hairpin resonators

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An on-chip implementation of a W-band filter with dual notches at 82 GHz and 95 GHz is presented. Reflection mode filtering methods are implemented with dual hairpin resonator networks, using the inherent parasitic losses in the resonators to create matched loads at the stopband frequencies of interest while reflecting passband power. Notches of 6 dB and 10.6 dB stopband insertion loss, and 3.7% and 5.6% relative bandwidths respectively, were achieved. This represents the first implementation of reflection mode filtering in the W-band on-chip.

Introduction: The mm-wave spectrum has the potential to host an array of wireless communications channels with high data rates [1]. Regions in the W-band between 75 GHz and 110 GHz have been allocated mostly to fixed and mobile communications channels [2], taking advantage of the local minimum in atmospheric attenuation [3]. However, this band would be divided by multiple narrow bands used for active earth exploration and space research, such as the 94 GHz band reserved exclusively for active space exploration and cloud monitoring [4]. If suitable notch filters are included in a mm-wave communications transceiver, wideband front-ends can be defined and implemented as opposed to narrowband channels either side of a reserved band.

Waveguide filters [5, 6] have been implemented to realise mm-wave notch filters with relative bandwidths as narrow as 0.81%, but are not suited for handheld communications equipment. Since mm-wave resonators are small enough to fit on-chip [7], monolithic back-end-of-line (BEOL) metallization stackups would allow for the manufacture of single chip mm-wave transceivers. Thus far only wideband bandpass mm-wave filters have been synthesised on-chip [8].

On-chip resonators are, however, characterised by low quality factors (Q-factors) [7], which hamper the implementation of conventional transmission line coupled resonator notch filter topologies such as capacitively coupled shunt stubs [9], high impedance connected shunt stubs [9, 10], parallel resonators [10] and L-resonators [11].

Reflection mode dual-phase path filters use identical resonators (with loss intentionally included) to selectively reflect signal power at the two outputs of a single -3 dB quadrature hybrid [12, 13]. Outside of resonance, the resonators reflect energy, which combines in-phase at the isolated port, but cancels out-of-phase at the input port. Since no signal power returns to the input port, the filter is matched at all frequencies. At resonance, the resonators act as matched loads to dissipate the incident energy, requiring lossy resonators to be used.

Given the inherent low Q-factors of resonantors on-chip, this circuit is ideal for implementation in a BEOL stackup. In other substrate media, loss may need to be artificially introduced. This paper investigates such use of inherent losses in on-chip transmission lines to realise a reflection mode notch filter. The effect of using two identical coupled resonators to create multiple notches at even and odd mode resonant frequencies is also investigated.

Hairpin resonator geometry: Microstrip half-wavelength hairpin resonators with identical capacitive gaps, w_{cap}, track widths, w_{res}, and lengths, l_{res}, as shown in Fig. 1, were chosen given their compact geometry [14]. Dual even and odd mode resonances were created through tight coupling (controlled by w_{g2}), as shown in Fig. 2 for resonators with an uncoupled resonant frequency of 87 GHz.

The input coupling has negligible effect on the resonant frequencies for tight coupling, but instead adjusts the input impedance of the resonator set to match that of the incoming transmission line. The coupling coefficient as a function of w_{g1} is also shown in Fig. 2.

Circuit modelling: A circuit schematic of a dual notch reflection mode filter is shown in Fig. 3. The resonator unloaded Q-factor, Q_0, is inherent to the geometry as implemented in a chosen technology process. The input coupling coefficient must be chosen such that the input impedance of the coupled resonators match that of the -3 dB quadrature hybrid port at either resonant frequency. This is modelled as a mutual inductance, M_{01} [15], between half the first resonator inductance and the inductance formed by the open circuited transmission line leading from the quadrature hybrid. The interresonator coupling coefficient can also be modelled by a mutual inductance, M_{12}, between the unloaded resonator circuit models. This forms even and odd mode resonant frequencies, hence a dual notch response.

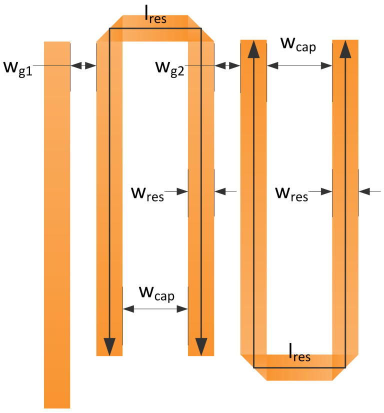

Fig. 1 *Adjustable parameters of identical hairpin resonators and independently tunable coupling gaps*

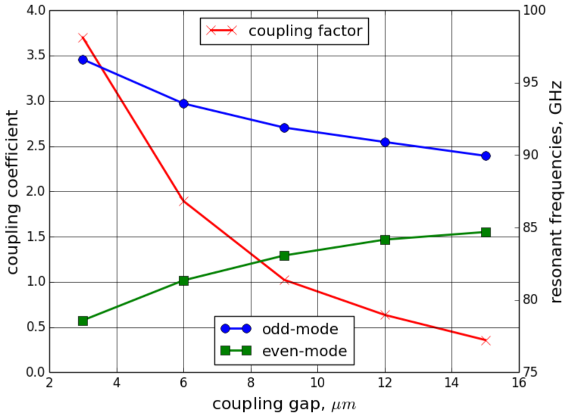

Fig. 2 *Even and odd mode resonant frequencies obtained from tightly coupled hairpin resonators, as well as input coupling coefficients obtained, as functions of respective coupling gaps*

Synthesis and simulation: A notch filter with stopbands at 81 GHz and 94 GHz is synthesised to block unwanted signals from active space and earth exploration activities. A nominal hairpin resonator with centre frequency of 87 GHz, which is set by adjusting w_{cap} and l_{res}, and Q-factor of 30, which is limited by the technology process, was chosen for this design. From Fig. 2 it can be seen that a nominal interresonator coupling gap of 5.5 μm is required for the intended dual notch frequencies. From circuit simulation, an input coupling value of 3.7 provided the best trade-off between critical coupling to each of the two coupled resonanting modes. A deeper notch was designed for use at 94 GHz since cloud monitoring takes place in this band. Using the 3D full-wave electromagnetic (EM) solver in CST Microwave Studio, the geometric parameters were fine tuned to provide the desired insertion loss response shown in Fig. 4. The final parameters were chosen as l_{res} = 1003 μm, w_{res} = 18.2 μm, w_{cap} = 50 μm, w_{g1} = 3 μm and w_{g2} = 5 μm.

Manufacturing and measurement: The IHP SG13 BEOL process was chosen for implementation given the thicker topmost metal layer, which would decrease the transmission insertion loss of the quadrature hybrid. The manufactured die is shown in Fig. 5.

The measured results were obtained using calibrated Ground-Signal-Ground (GSG) probes and deembedded using Thru-Reflect-Line (TRL) standards placed on the right hand side of the die in Fig. 5. The networks were assumed to be symmetrical and reciprocal during deembedding. The simulated and measured results are compared in Fig. 4 and Table 1. The transmission lines' geometric taper [16], which was not included in the full-wave EM simulation, may have influenced the fringe capacitance at

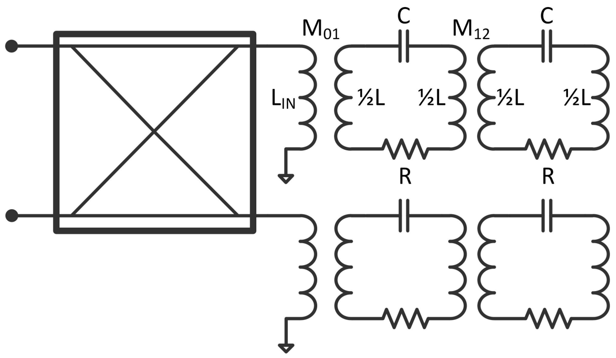

Fig. 3 *Circuit schematic of reflection mode dual phase path notch filters with lossy bandpass resonators*

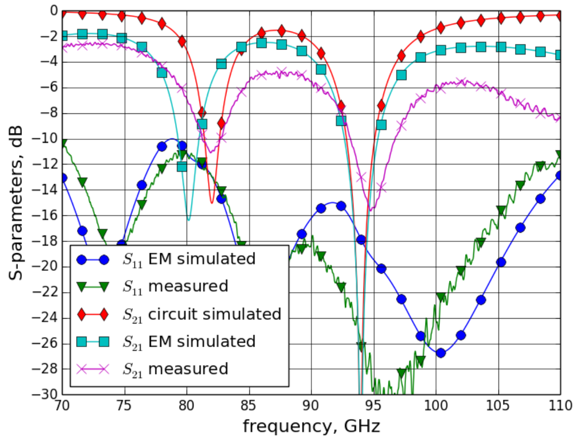

Fig. 4 *Return and insertion loss magnitude responses of the reflection mode notch filter*

the endpoints of the transmission line resonators and is believed to have caused the variation in centre frequencies. The taper also influenced both the external and internal coupling, resulting in mismatch at resonance and henceforth shallower notches. The additional frequency dependent insertion loss mechanism seen in the measured results is believed to be due to unmodelled surface roughness [16]. The measured return loss, $|S_{11}|$, was below -10 dB for all frequencies under consideration; the filter was therefore matched at all frequencies.

Table 1: Notch filter results

	Simulated result	Measured result	Variation
Centre frequencies f_0	80.1 GHz, 94 GHz	82 GHz, 95 GHz	2.4%, 1%
Bandwidths BW	4.6%, 5.8%	3.7%, 5.6%	24%, 3.4%
Notch depths	13 dB, 35 dB	6 dB, 10.6 dB	

Conclusion: It is shown that the low achievable on-chip resonator unloaded Q-factor can be leveraged to realise notch filters if a reflection mode topology is used. The possibility of dual notches, matched at all frequencies, is also achieved. The use of a full-wave EM solver for BEOL passives modelling is validated by 2.4% agreement between the simulated and measured notch centre frequencies. The achieved notch filter is the first implementation of reflection mode filtering both on-chip and in the W-band.

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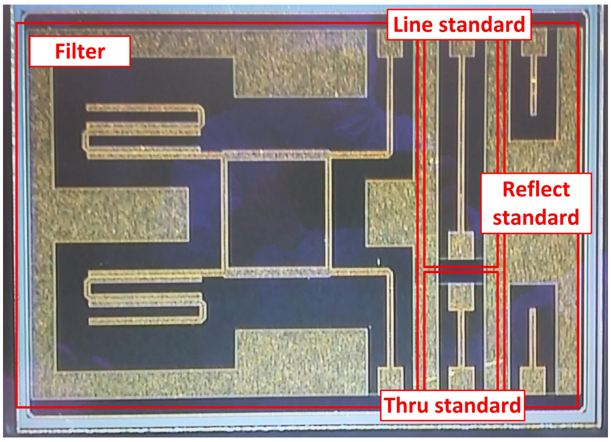

Fig. 5 *Manufactured reflection mode filter in the IHP SG13 BEOL technology process*

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