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| Citation | Holloway, Jack W. et al. "220-to-330-GHz Manifold Triplexer With Wide Stopband Utilizing Ridged Substrate Integrated Waveguides." IEEE Transactions on Microwave Theory and Techniques, 68, 8 (August 2020): 3428-3438 © 2020 The Author[s] |
|----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| As Published | 10.1109/TMTT.2020.2997367 |
| Publisher | Institute of Electrical and Electronics Engineers (IEEE) |
| Version | Author’s final manuscript |
| Citable link | https://hdl.handle.net/1721.1/129444 |
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220-to-330-GHz Manifold Triplexer With Wide Stopband Utilizing Ridged Substrate Integrated Waveguides

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Abstract—This article reports a three-channel, noncontiguous, manifold multiplexer operating from 220 to 330 GHz, a 40% fractional operating bandwidth. The structure is designed and implemented using a set of ridged substrate integrated waveguides (SIWs). The ridged SIW improves the stopband bandwidth and reduces the overall structure size by 35% over a conventional SIW design. The triplexer utilizes an organic package substrate technology developed by Intel, featuring four thick copper metal layers and continuous trench vias in lieu of standard via fences, which significantly decrease the ohmic loss of the ridged SIW waveguides. Electromagnetic-circuit modeling and codesign techniques are adopted in the development of the triplexer structure. The fabricated triplexer is measured using banded millimeter-wave wafer probing and exhibits 3 to 7 dB of insertion loss in the passbands and better than 10 dB of average return loss for each of the channel filters. The measured stopband attenuation is better than 27 dB for all three channels.

Index Terms—Channelizer, manifold multiplexer, multiplexer, ridge substrate integrated waveguide (SIW), terahertz, triplexer.

I. INTRODUCTION

With the growing interest in millimeter-wave and terahertz (THz) electronics, there has been an associated interest in the various components that are required to realize these systems. In [1], one application of these systems is described, in which guided and modulated sub-THz (approximately 220–330 GHz) waves are used to transport high-rate data over backplane-scale distances. Such a scheme is attractive for a number of reasons, including broad available fractional bandwidth, compact system size (driven by smaller wavelengths compared with lower frequency operations), relative robustness to misalignment during assembly versus optical systems, and lower transmission losses than those exhibited by copper lines for high-speed data transmission.

One of the challenges associated with the development of the above link system is the realization of compact, low-loss channelizers. The use of these components is a fundamental requirement to leverage the available waveguide bandwidths. While waveguide-based channelizers have been demonstrated at lower bands and waveguide components are available at higher operating frequencies, they are relatively large and require more expensive packaging and interface schemes. This type of scheme would require a planar integration approach to be economically feasible. On-chip implementation is one option: the use of transmission line-based structures in an integrated circuit (IC) back end of line (BEOL) can produce compact filters, but the loss associated with radiation and conductor resistance is a disadvantage. Substrate integrated waveguide (SIW) filters have been broadly investigated at lower frequencies [2]–[5] for their superior performance over other planar approaches. There are some published results of BEOL-integrated SIW structures for radiators in the sub-THz regime [6]–[11] and a smaller number related to transmission lines [12] and simple filters [13]. There are a few published SIW filter works utilizing LTCC or PCB materials at W-band [14], [15] and above [16]. In [17], a novel thick-film technology was used to demonstrate cavity filters at V-, W-, D-, and G-bands. In comparison to single filter topologies, the use of SIW topologies and techniques for RF multiplexers and channelizers has been relegated to lower frequencies [18], [19]. This may be attributed to the difficulty of designing both manifold [20] and star-junction [21] devices, as well as the design rules and tolerances in available processes.

This article discusses the design and measurement of a 220–330-GHz triplexer for the integration into a high data rate meter-class I/O scheme illustrated in Fig. 1. The concept is shown in further detail in the figure inset in which a flip-chip bonded IC with sub-THz transceivers is directly connected to an in-package multiplexer to combine (on transmit) and channelize (on receive) the modulated sub-THz wave. The multichannel sub-THz energy is coupled to/from the sub-THz
This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES

Fig. 1. Concept of a multichip module (MCM) in which high-rate data are aggregated and transported across a wideband sub-THz dielectric waveguide. Inset: exploded view of the concept with a broadband triplexer, directly coupled to solder bumps, each driven by an electronic sub-THz transceiver. The combined energy is coupled into a sub-THz waveguide via a broadband coupler. The triplexer structure is outlined in the dotted black line within the inset.

waveguide via a wideband planar coupler [6]. To the best of our knowledge, there was previously no work utilizing SIW structures for channelizing sub-THz signals.

This triplexer is implemented in a new organic packaging process technology developed by Intel Corporation. This new process features thick copper layers, continuous via bars/trenches, and flexible design rules. The channelizer, based on a manifold topology [20], [22], uses ridged SIW structures for the individual channel filters and includes broadband ground–signal–ground (GSG) transitions for direct wafer probing. The device is designed for three 30-GHz-wide passbands with 10-GHz guard bands between channels.

II. ORGANIC PACKAGING PROCESS

The triplexer presented in this work is fabricated on an IC organic packaging process developed at Intel Corporation employing laminate panels of $\sim 500 \times 500 \text{ mm}^2$ area. The fabrication process is a modified semiadditive microelectronics packaging process (SAP) that allows the creation of continuous and arbitrary shape interlayer trench vias. A high-level fabrication flow of a semiadditive microelectronics packaging process is shown in Fig. 2(a). The process starts with a patterned copper clad core (CCL) with through holes (step 1). Next, the dielectric buildup film is laminated (step 2). Laser via drilling, cleaning, and seed deposition follows (step 3). Via and trace formation are performed via plating and etching (step 4). Steps 2–4 are repeated for $N$ metal layers. Finally, solder-resist layer deposition and patterning are performed (step 5).

The developed stack-up features a total of eight metal layers and three buildup dielectric layers around each side of a thicker substrate core. The buildup layers feature low-loss organic-based materials with inorganic fillers, while the top and bottom sides of the fabricated package are covered by a solder-resist layer. The dielectric layer and the core layer thicknesses targeted are 30 and 200 $\mu$m, respectively. The targeted copper thickness is 15 $\mu$m. Continuous trench vias, favored for the implementation of low-loss SIW structures, are enabled through lithographic processes. These via layers target 30 $\mu$m in thickness. Fig. 2(b) shows a cross section of the metal layers (M1–M4) and interlayer vias (V1–V3) utilized in this article. A ridge structure is also shown in the figure.

III. TRIPLEXER DESIGN

The triplexer is designed to match to 50 $\Omega$ at all ports and has three 30-GHz-wide channels: 220–250 GHz (Channel 1), 260–290 GHz (Channel 2), and 300–330 GHz (Channel 3). For the application described in Fig. 1, less than 5 dB of passband insertion loss and better than 10 dB return loss are desired. To prevent cross-channel interference, more than 30 dB of stopband attenuation and better than 40 dB of interchannel isolation are also required.

Fig. 3 shows a 3-D model of the final triplexer design. The structure makes use of ridged SIW resonator sections, as described in Section III-A. The individual channel filters and the manifold (common) ports are excited with wideband transitions from GSG probes [see Fig. 3 (upper right inset)]. This transition is described in Section III-B. Finally, a very fast circuit-EM codesign scheme is described in Section III-C to finalize the triplexer dimensional parameters.
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A. SIW Versus Ridged-SIW

Due to the large range of frequencies over which the triplexer must operate, consideration must be given to the spurious passband present in a bandpass filter utilizing a conventional SIW with a rectangular cross section [23], [24]. This leads to an unwanted interaction between Channels 1 and 3. In order to ameliorate this problem, a ridged-waveguide topology is adopted, which takes advantage of the wider frequency range over which only the lowest order mode is allowed to propagate [25], [26]. A ridged waveguide has a wider spurious-free passband region over the conventional rectangular waveguide (RWG). Since the cross-sectional circumference of a ridged waveguide is much longer than an RWG due to the additional ridge inside the waveguide, the associated cutoff frequency is much lower than that of the RWG with the same size. Due to an irregular shape of the inside of the ridged waveguide [see Fig. 2(b)], the transverse resonance method can be used to analyze the structure. The cutoff frequency of a single ridged waveguide can be found by using [27]

\[
    f_c = \frac{1}{2A_1 \sqrt{\mu \varepsilon}} \cdot \frac{2}{\pi} \sqrt{\frac{A_1 B_2}{A_2 B_1}} \cdot \frac{1}{1 - \frac{A_2}{A_1}}
\]

where \( \mu \) and \( \varepsilon \) are the permeability and permittivity of the process dielectric material, and \( A_1, A_2, B_1, \) and \( B_2 \) are the guide dimensions shown in the inset of Fig. 3. In addition, the gap between the top surface of the ridge and the waveguide ground surface has a strong electric field; this capacitive loading increases the cutoff frequency of the next higher mode operation compared with the case of an RWG-based resonator. Such a cutoff frequency can be modified by the values of these dimensional parameters \( B_2 \) and \( A_2 \). By leveraging this wider fundamental-mode bandwidth provided by ridged-waveguide resonators, we realize higher spurious-free stopband suppression than with conventional RWGs (or SIWs). However, the structure does incur additional insertion loss over conventional RWG-based filters.

As the packaging process provides access to variable ridge heights by using different metal layers, a parametric eigenmode analysis using HFSS [28] is carried out to determine the optimal dimensions for the maximum quality factor \( Q \) of an idealized resonator geometry. An overall guide width of \( A_1=300 \ \mu m \) [see Fig. 3 (inset)] and height of \( B_1=120 \ \mu m \) (utilizing the full process stack) are adopted. A ridge width of 50% of the overall waveguide width (to meet spurious passband requirements) and a ridge height of 90 \( \mu m \) (commensurate with the M3 metal layer) are found to provide the highest available \( Q \); between 233 and 238 across the entire triplexer operating band, including dielectric and conductor losses. These dimensions were used on the subsequent channel filter and triplexer designs. Fig. 4 shows the waveguide dispersion results of an eigenmode simulation in which the normalized propagation constants \( \beta/k_0 \) of the first two modes are plotted.
As can be seen, only the lowest-order mode is supported from 130 to 410 GHz using this ridged SIW cross section, providing 280 GHz of available single-mode bandwidth—far more than the 110 GHz required in this channelizer design. Rectangular SIW dispersion characteristics are also shown for comparison. In this case, the ridged cross section provides a 67% more single-mode bandwidth than the rectangular SIW.

For comparison, a conventional RWG-based SIW filter and a ridged-SIW-based filter, both having eight sections and eight passband poles, are designed using FEST3D [29]. Both filter designs maintain compatibility with the dimensions available in the organic packaging process described in Section II, and they are optimized to meet the same passband bandwidth, insertion loss, match, and adjacent band suppression figures. As shown in Fig. 5(a), the ridged SIW filter is ∼40% more compact. The resultant 3-D structures are simulated using HFSS. The simulated S-parameters are shown in Fig. 5(b) and verify that the ridged-SIW topology indeed improves the spurious passband performance by >50 dB and increases the adjacent channel stopband suppression by ∼10–25 dB across the 260-to-290 GHz band.

B. Wideband Ridged-SIW to GSG Transition

In order to measure the triplexer in the WR-3.4 band, transitions to GSG pads for on-substrate probing had to be integrated. To facilitate rapid design, a single wideband transition was designed into the packaging process, simultaneously providing the pads for probing, waveguide mode conversion, and impedance matching. An approach based on the technique presented in [30] was used. In the previous work, a short section of slot line was used to produce the match between a GSG probe and an SIW at W-band. As the presented triplexer operates over a large fractional bandwidth (40%), a broader bandwidth match was required.

Fig. 6(a) shows the transition structure. The top metal layer was used to realize the pad landings. The pads are terminated with broadband opens realized as circular slots. The interposer process provides flexible conductor design rules, including curved geometries. This flexibility allows for the design of this type of broadband open termination. A symmetric lumped port
A waveguide cross section was first set (rapidly converge on a set of design parameters. In this case, and similar to that presented in [18] and [31], was utilized to filters.

Four manifold spacing lengths between each of the channel iris widths and ten waveguide lengths per channel filter and tuning over at least 61 parameters. This figure includes nine eight-pole channel filters, the overall triplexer would require and expensive. Assuming a triplexer utilizing asymmetric complicated electromagnetic structures can be time consuming.

C. EM-Circuit Model Codesign

Full-wave parametric design and optimization of complicated electromagnetic structures can be time consuming and expensive. Assuming a triplexer utilizing asymmetric eight-pole channel filters, the overall triplexer would require tuning over at least 61 parameters. This figure includes nine iris widths and ten waveguide lengths per channel filter and four manifold spacing lengths between each of the channel filters.

Instead, a method, which is based on an EM-circuit codesign mimicking the wafer probe is used to excite the GSG pads. The values of the dimensional parameters [as illustrated in Fig. 6(b)] of the transition are listed in Table I.

Fig. 7 shows the simulated S-parameters of the transition. Across the entire 200-to-320-GHz band, the return loss is better than 8 dB, and the insertion loss is better than 3 dB. The slight mismatch below 250 GHz and above 320 GHz was compensated in the final design by absorbing the transition response into the final triplexer end-to-end response.

\[
A_1 = 300 \text{ \mu m} \quad A_2 = 150, \\
A_3 = 45.7 \quad R = 130, \\
D_x = 93.5 \quad L_{\text{match}} = 330, \\
W_d = 43.1 \quad W_p = 35, \\
W_s = 33.8 \quad \Delta P = 113.
\]

TABLE I
DIMENSIONS OF THE GSG PADS TO RIDGED-SIW TRANSITION

| Parameter | Dimension (\mu m) | Parameter | Dimension (\mu m) |
|-----------|-------------------|-----------|-------------------|
| \(A_1\)   | 300               | \(A_2\)   | 150               |
| \(A_3\)   | 45.7              | \(R\)     | 130               |
| \(D_x\)   | 93.5              | \(L_{\text{match}}\) | 330               |
| \(W_d\)   | 43.1              | \(W_p\)   | 35                |
| \(W_s\)   | 33.8              | \(\Delta P\) | 113               |

Fig. 7. Full-wave simulated S-parameters of the wideband GSG-to-ridged-SIW transition, designed in the interposer process. Port 1 corresponds to the GSG probe port, and port 2 corresponds to the ridged SIW port.

The resultant parameterized S-parameter files are used in a circuit simulator to model the reactive response of the iris, \(S_{\text{W1k}}\) corresponding to the frequency response of the kth iris in the ith filter with iris opening width \(W_{i,k}\) (see Fig. 9). The responses of lengths of ridged-SIW (corresponding to parameter \(L_{i,k}\) in Figs. 9 and 10) are based on a port-only full-wave solution for the guide cross section, with the propagation constant and attenuation (\(\beta\) and \(\alpha\), respectively) extracted. These transmission line responses are modeled in the same circuit simulator, parameterized by guide length. These parameterized iris responses were integrated into a full triplexer circuit model (see Fig. 10) incorporating the wideband GSG probe transition \(S_P\) and the T-junction response \(S_T\).

Each channel filter is connected through a certain length of single-ridge waveguide (\(L_{i,1}\) in Fig. 10) to provide a proper phase compensation between channel filters. The connecting manifold lengths (\(L_{32}, L_{21}\), and \(L_{\text{short}}\)) are determined to provide an open-matching in the center frequency of the neighboring channels.

Interpolation of the previously generated iris responses, \(S_{\text{W1k}}\), was utilized in the S-parameter circuit simulation to rapidly optimize the triplexer parameters in the circuit domain. The triplexer was optimized for a flat passband and return loss. A 10-GHz guard band was utilized between each channel, and the design was optimized for better than 10-dB return loss at the output of each channel filter. The resultant circuit simulator-generated dimensions were utilized in a fully parameterized full-wave model of the overall design (as shown in Fig. 3). The results for both the circuit-EM model and the full-wave model are plotted in Fig. 11. It should be noted that no postcircuit-design optimization was done utilizing the full-wave model. As the full-wave simulation of the entire triplexer structure required orders of magnitude more time (more than an hour compared with fractions of a minute when utilizing the circuit model), further full-wave optimization was not practical. The results show excellent agreement between the two simulated responses.
Fig. 9. Top view of a full-wave model of a parameterized, asymmetric, eight-pole ridged-SIW bandpass filter utilizing inductive iris coupling. The structure’s top copper layer is removed in this view to reveal structure within the filter.

Fig. 10. Circuit model used in the EM-circuit codesign of the presented triplexer. Each bandpass filter is composed of fully parameterized lengths of waveguide and S-parameters, parameterized by width, representing the inductive irises.

The manifold reflection $\Gamma$, as shown in Fig. 11, shows a good match across all the designed passbands, with a reflection between the passbands. This is expected given the noncontiguous design. In addition, the full-wave model was used to generate plots of the magnitude of the $E$-field on all the device conductors in Fig. 12. The three plots demonstrate the passband characteristics of the device at the designed center frequencies of the three channels. Fig. 12 also demonstrates that the channel filters effectively suppress the out-of-band energy injected into the channelizer from the manifold or the other channel filters.

IV. EXPERIMENTAL RESULTS

A. Fabrication

All designs were fabricated at a facility in Intel Corporation, Chandler, AZ, USA. The process provides a feasible means to realize highly scalable, higher performance electromagnetic structures. Fig. 13(a) shows a fabricated panel, sized 500 mm $\times$ 500 mm, made up of copies of designed test structures. A 3-D X-ray view of the fabricated triplexer is shown in Fig. 13(b). A photograph of a portion of the fabricated devices, with the triplexer and individual channel filter locations denoted, is shown in Fig. 14. The GSG pads and the wideband ridged-SIW transitions implemented in the top copper layer are revealed through the solder-resist layer openings.

B. Individual Channel Measurements

Three individual channel filters [see Fig. 14 (left)] incorporating wideband GSG transitions on both sides of the filter structure were fabricated and measured. These filter designs are identical to the channel filters optimized for use in the triplexer. When measuring the individual channel filters, the probes are colinear. This colinear geometry also allows the use of standard one-tier probe calibration using commercially available calibration standards.

The measured and simulated data are plotted in Fig. 15. There is good agreement between the number and location of the passband poles, indicated by the location of the resonances in the input reflections ($S_{11}$, $S_{22}$)—especially in the lower two channels. The measured data are within 2–4 dB of the simulated passband $S_{21}$ in the bottom two channels. The top channel [see Fig. 15(c)] demonstrates a larger discrepancy between the simulated and measured data of up to 7 dB in the mid-band.

Unanticipated out-of-band resonances can be seen in all three measurements ($S_{11}$, $S_{22}$, and $S_{21}$) outside of the individual channel passbands. For example, in Fig. 15(a), we see a discrepancy due to a passband pole at approximately 260 GHz. Similarly, in Fig. 15(b), unintended passband poles are placed outside the desired passband (260–290 GHz) at approximately 240 and 305 GHz. We also see an unintended transmission in channel 3 [see Fig. 15(c)] at approximately 255 GHz. Given the exact number of resonators in each filter, we assess that these unanticipated portions of the responses
Fig. 12. Plot of the E-field intensity on the triplexer conductor surfaces at (a) 235, (b) 275, and (c) 315 GHz. These frequencies correspond to the centers of the three passband channels.

Fig. 13. (a) Fabricated 500 mm × 500 mm panel made up of repeated test designs. (b) 3-D X-ray image of the fabricated triplexer on Intel’s organic packaging process. Note that the top and bottom metal layers have been intentionally hidden to allow a view of the internal ridges and SIW resonator cavities.

Fig. 14. Micrograph of the standalone channel filters (left) and the complete triplexer (right).

C. Triplexer Measurement

The frequency of operation precludes performing measurements with more than two ports. In addition, the design did not include resistors, and the use of discrete resistors at these frequencies is impractical. These factors dictated two-port measurements with the remaining device ports unterminated (open).

As can be seen in the photograph in Fig. 14, the manifold and individual channel filters in the triplexer are not colinear. The device testing is done via 100-μm-pitch wafer probes; at these frequencies, no commercially available calibration substrates are available that account for the 90° relative orientation between the channel filters and the triplexer manifold. Instead, a tiered calibration scheme was utilized to calibrate the probe tips. As described in Section III, the response of the wideband GSG probe to ridged-SIW transition was absorbed into the overall triplexer response. This allows the full device response to be tested by simply calibrating the wafer probe tips.

The test setup, pictured in Fig. 16, consists of a Keysight PNA-X four-port Vector Network Analyzer (VNA), two Virginia Diodes (VDIs) WR-3.4 frequency extenders, and two Cascade Infinity WR-3.4 GSG probes. Several straight sections...
Fig. 15. Comparison of three individual channel filters, with wideband GSG transitions at both ends of the filters. (a) Channel 1 (220–250 GHz). (b) Channel 2 (260–290 GHz). (c) Channel 3 (300–330 GHz). The measured data is depicted as the solid line, with the corresponding full-wave simulation results shown as dotted lines. The forward transmission ($S_{21}$) and both ports’ reflection ($S_{11}$ and $S_{22}$) are plotted.

Fig. 16. Wafer-probe characterization of the triplexer.

of WR-3.4 and $H$-plane bends are used to position the waveguide probes appropriately for testing the triplexer.

When measuring the triplexer design, a multitier calibration scheme (including an unknown-through calibration [32]) is used to deembed the measurement setup from the device measurement.

1) A small section of WR-3.4 bend is characterized ($S_{\text{bend}}$) independently after performing a two-port flange-flange calibration on a separate setup. The phase response of this section will be used in the subsequent unknown-through calibration.

2) Each VNA extender calibrated to the waveguide flange using a vendor-supplied waveguide calibration kit.

3) Each probe ($S_{\text{left}}$ and $S_{\text{right}}$) is characterized using the previous flange calibration to a set of vendor-supplied short, open, and load (SOL) standards on a calibration substrate.

4) The waveguide sections are attached to the VNA extenders up to the probes; the probes are not connected. A two-port unknown through calibration is utilized to move the calibration plane up to the probe flanges.

5) Finally, the probes are mounted, and the measured $S_{\text{left}}$ and $S_{\text{right}}$ responses for the left and right probes are used in the VNA to perform the final layer of deembedding to the probe tips.

At this point, the measurement setup is calibrated to a reference plane at the probe tips. The two-port device measurements can be taken. To account for larger calibration errors that were observed for wideband calibrations (compared with a test standard), this process was carried out for three sets of measurements. Each calibration and measurement covered 50 GHz of bandwidth: 220–270, 250–300, and 280–330 GHz. Each waveguide calibration was followed by the measurement of an offset short standard to ensure good calibration across the observation bandwidth. The plotted response includes averaging of those overlapping portions of the bands from each measurement (i.e., 250–270 and 280–300 GHz).

The simulated full-wave response in Fig. 11 is based on 50-$\Omega$ ports connected to all four triplexer ports. This full-wave four-port was simulated in three separate situations in Keysight ADS with the manifold (input) port connected and one of each of the channel filter ports connected. These simulated channel responses are plotted against the measured response in Figs. 17 and 18.

The frequency band is limited to no lower than 220 GHz due to the VDIs VNA extender and the available waveguide probes (WR-3.4) in the test setup. Fig. 17 shows the measured and simulated transmission of a two-port response of the triplexer structure; this represents a measurement (or simulation, shown with the dashed line) between the manifold and the associated channel filter output port. The other ports are unterminated.
in resonator frequency and interresonator coupling. These could arise from small changes in fabricated dimensions or differences between modeled and fabricated material dielectric properties. Probe-landing locations can also be a source of inconsistency in the measurements. However, large changes in the measured responses were not observed with different positioning of the probes relative to the wideband transition pad openings. This may be attributed to the highly confined nature of these ridged-SIW structures and well-designed port matching.

V. Conclusion

The measured channel filters and triplexer responses demonstrate the efficacy of the presented device and design methodology. To the best of our knowledge, this represents the first published instance of a ridged-SIW multiplexer implemented at these frequencies and operating over the demonstrated bandwidth. Furthermore, this work represents the first measured devices on an organic packaging process featuring continuous trench vias. Finally, this work also represents the best performance at these frequencies for these types of devices implemented in organic packaging technologies.

While the authors are unaware of any comparable published multiplexer implementation for this sub-THz application, the closest comparison in Table II is that shown in [33] though that work does not include any measurement results. It is a three-band channelizer over 525–625 GHz. However, the multiplexer bandwidth is 17% (compared with the 40% in the presented work) due to the narrow channel filter bandwidth. As was discussed in Section I, the device operating band is of the utmost importance. As such, fractional bandwidth of the multiplexer is an important figure of merit. The remaining comparisons [34]–[36] are sub-THz band single-channel filters and are listed to compare the fractional bandwidth of the single filter with our channel filter design. We note [35], in particular. This work compares favorably from a channel-filter perspective. However, as described in Section III-A, the spurious passband performance precludes the realization of wide operating band triplexers.

The device performance can, in the future, be improved by carefully characterizing the process material properties in the designed band along with the achievable fabrication tolerances and variations. These factors can be used to future improve the design of the channel filter and overall triplexer response by ensuring the location of the passband zeros. We expect that this will not only improve passband insertion loss and channel-to-channel isolation but also improvement manifold and channel filter matching.

The presented devices along with Intel’s organic packaging process provide an attractive option for new, low-cost, high-performance, in-package filters, and multiplexers that can be readily integrated with existing IC infrastructure. The availability of these components can enable the realization of new millimeter-wave and THz systems.

ACKNOWLEDGMENT

The authors would like to thank Dr. Chris Galbraith at Intel Lincoln Laboratory, Dr. Luciano Boglione, and Dr. John...
Rodgers at the Naval Research Laboratory for many helpful technical discussions. They would also like to thank Dr. Aleksandar Aleksov and the Substrate Process Technology Development Team, Intel Corporation, for the fabrication support.

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