300-GHz-band diplexer for frequency-division multiplexed wireless communication

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SUMMARY We propose a novel silicon diplexer integrated with filters for frequency-division multiplexing in the 300-GHz band. The diplexer consists of a directional coupler formed of unclad silicon wires, a photonic bandgap-based low-pass filter, and a high-pass filter based on frequency-dependent bending loss. These integrated filters are capable of suppressing crosstalk and providing >15 dB isolation over 40 GHz, which is highly beneficial for terahertz-range wireless communications applications. We have used this diplexer in a simultaneous error-free wireless transmission of 300-GHz and 335-GHz channels at the aggregate data rate of 36 Gbit/s.

**key words:** diplexer, frequency-division multiplexing, silicon waveguides, terahertz, wireless communications

1. Introduction

Silicon dielectric waveguides have been investigated as a promising terahertz (THz)-wave transmission line [1]-[4]. Compared to conventional metallic transmission lines, which suffer from the increasing propagation loss caused by the skin effect at such high frequencies, silicon dielectric waveguides have been proven to exhibit lower loss, broadband operation, and reduced cost. Effective-medium cladded silicon waveguides are capable of changing their dielectric characteristics depending on the cladding conditions [3], while unclad silicon waveguides have the advantages of greater control over physical geometric parameters such as curvature and separation between coupled lines [4]. These waveguides make it feasible to create integrated functional components including filters and beam splitters in the THz band.

In this context, THz communication systems using silicon dielectric waveguides have been reported in recent years [5, 6]. With the aim of utilizing the wide bandwidth efficiently, we have previously investigated frequency-division multiplexing (FDM) using a silicon diplexer [4], [6]-[8] and a multiplexer [9]. In the cited work [8], we developed a 600-GHz-band unclad silicon diplexer and achieved a 16-Gbit/s error-free two-channel wireless transmission. One of the obstacles to a higher data rate is considered to be crosstalk, which negatively impacts channel quality. In order to achieve FDM communications, we require high isolation at center frequencies, as well as a sharp band-edge and rapid roll-off in order to suppress crosstalk across the channel bandwidth. This can be achieved by THz filters. Our preliminary work reported the results of the communications experiment using the diplexer with integrated filters [10], and here we expand our report to include detailed information about the design and electromagnetic principle of operation of the filters that are integrated in the diplexer.

2. Integrated Terahertz Filters

The proposed diplexer is composed of a directional coupler, a low-pass filter, a high-pass filter, and a protective frame, which all are fabricated from a single 200-μm-thick high-resistivity (> 10 kΩcm) silicon wafer. The protective frame includes the effective medium with periodic cylindrical holes with 55-μm radius and 120-μm period, providing physical support and total-internal-reflection-based field confinement. This field confinement prevents electromagnetic coupling to the solid portions of the frame. The frame also facilitates convenient handling with tweezers. In this section, each filter is individually designed and evaluated, and is reported.

2.1 High-pass Filter

For dielectric unclad waveguides, bending loss is frequency-dependent due to the delocalization of modal fields at lower frequencies. When the waveguide bends, the radiation of weakly-confined low frequencies is increased, and this effect can be exploited to realize a convenient high-pass filter [11]. Here, we employ two such narrowed bends to enhance roll-off and isolation. In order to avoid undesired reflections, an 800-μm-long linear taper progressively reduces the guide width W from 220 μm to 170 μm. The high-pass filter is experimentally characterized with the metallic case that includes WR3.4-hollow-waveguide input/output (I/O) ports. The results are given in Fig. 1(b), showing good agreement with the results of electromagnetic simulations, and confirming the high-pass effect caused by narrowing the guide; the 3-dB cutoff frequency has increased from 263 GHz to 310 GHz.

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2. Low-pass Filter

The low-pass filter is implemented with a longitudinal array of cylindrical air-holes that act as a one-dimensional photonic crystal, as shown in Fig. 2(a). The reflections from all scatters constructively interfere, thereby forming a Bragg mirror, or photonic bandgap, which is a frequency range within which no propagation modes are permitted [12]-[14]. By tailoring the resultant stopband to the upper end of the operation bandwidth, a low-pass filter is realized. The frequency response of the filter is determined by the structure of the hole array. Specifically, larger holes yield stronger isolation, but this comes at the expense of increased reflection due to mismatch with the waveguide. To address this, hole radii are gradually increased from 15 µm at the input and output to 65 µm in the center, for progressive matching. The separation between the holes determines the stopband and is varied from 180 µm to 210 µm in order to compensate for the change in radius. The total number of holes is 19, which is associated with the frequency selectivity and roll-off. The measurement results with the metallic case are given in Fig. 2(b). The results show good agreement with the results of electromagnetic simulations, indicating that even the smallest holes were successfully fabricated with high precision. The high isolation of 30 dB is obtained in the frequency range of over 330 to 360 GHz with a fast roll-off owing to the strong rejection of a Bragg mirror formed of the one-dimensional photonic crystal structure.

3. Diplexer with Integrated Filters

The design of the proposed diplexer is shown in Fig. 3(a). We employ an evanescent directional coupler formed of a pair of unclad silicon wires separated by a micro-scale air gap [4, 6, 8]. Low frequencies are transferred across the airgap more quickly, while high frequencies mainly remain the original waveguide. Thus, the original waveguide carries the high-frequency channel, and the coupled guide carries low-frequency channel. The width of a silicon wire is 220 µm, and the coupling length and distance are 1200 µm and 55 µm, respectively.

The filters described in Section II are monolithically integrated together with the evanescent coupler in order to reduce crosstalk. The original waveguide coming from the input port is gradually narrowed from 220 µm to 170 µm at the point whereafter electromagnetic waves are separated by the directional coupler. The low-pass filter is designed as the same described above except for the number of holes, which we increase to 21 in order to sharpen the filter’s roll-off.

The diplexer is housed within a bespoke metal package that offers WR3.4-hollow-waveguide port interfaces, and is experimentally characterized. Port 4 shown in Fig. 3 is terminated with a horn antenna that radiates all incident power to free-space, and hence functions analogously to a matched load, which simply removes power from the circuit. The results are given in Fig. 3(b), showing good agreement with the results of electromagnetic simulations. The
measured insertion losses $S_{21}$ and $S_{11}$ are less than 3 dB over 270 to 312 GHz and over 326 to 360 GHz, respectively. The isolation of the high-pass filter is approximately 30 dB in the vicinity of the center of the channel, and exceeds 15 dB in the frequency range from 260 to 300 GHz. Meanwhile, the isolation of the low-pass filter exceeds 40 dB in the frequency range from 335 to 360 GHz, showing rapid roll-off owing to the strong rejection of the one-dimensional photonic crystal structure. A comparison is also given between the filter-integrated diplexer and a simulation of a diplexer without filters, indicating that the frequency band that has the high isolation of over 15 dB is improved from 8 GHz to 40 GHz for high-frequency channel, is obtained over 30 GHz for low-frequency channel. The high isolation of these filters is expected to eliminate crosstalk in FDM communications.

![Diagram](image)

**Fig. 3** (a) Designed filter-integrated silicon diplexer. (b) Measured and simulated S-parameters compared with the diplexer without filters.

### 4. Communication Experiment

We conducted a 300-GHz-band wireless communication experiment with FDM scheme at a distance of ~1 cm as shown in Fig. 4. The diplexer packaged in the metallic case with WR3.4-hollow-waveguide I/O ports can easily be connected to THz components and used on the receiver side, as shown in Fig. 4(b). We additionally applied an optical receiver system [15], which enables us to select 300 GHz and 335 GHz as carrier frequencies in order to increase spectral efficiency. Overlapped signals between 300 GHz and 335 GHz are eliminated by optical filters that only extract single sidebands.

On the transmitter side, optical beating signals from two continuous-wave laser diodes were modulated by an electro-optic intensity modulator (IM). Then, two uni-traveling-carrier photodiodes (UTC-PDs) generated THz waves with carrier frequencies of 300 and 335 GHz. They were combined by a Y-junction coupler. Incidentally, a Y-junction inherently causes 3-dB loss apart from propagation loss, which is avoided by the diplexer with 1-dB loss around the operation frequency band. However, in this work the Y-junction was employed owing to its flat frequency response. After THz signals combined, they were radiated by a horn antenna. Subsequently, they were received and divided by the diplexer, and each channel was down-converted to IF signals by an individual sub-harmonic mixer (SHM) using a heterodyne detection scheme. The LO frequencies were 282 GHz for low-frequency channel and 353 GHz for high-frequency channel, and IF was 18 GHz for both channels. The IF signals were then up-converted to single-mode optical signals by an optical intensity modulator, IM. The bias voltage applied to the IM was set to the null point to suppress the laser carrier and sideband signals. Next, only single sidebands of the IF signals were filtered, and the filtered IF signals were detected by each baseband photodiode (PD) to obtain the data signal.

Figures 5(a) and 5(b) show the bit error rate (BER) characteristics for low-frequency channel and high-frequency channel, respectively, with the data rates of 15 Gbit/s and 18 Gbit/s. Error-free (BER < $1 \times 10^{-11}$) transmission was achieved up to 18 Gbit/s. Comparing the BER of low-frequency channel to that of high-frequency channel, there is no significant difference in the dependence on the transmission power. Clear eye diagrams were also observed at the data rate of 18 Gbit/s with two channels simultaneously. However, a BER degradation was observed at 18 Gbit/s between single-channel and simultaneous communications. It is considered to be caused by harmonics that occurred at the first data modulation, which interfere the adjacent channel even if only single sidebands are extracted by the optical filters.

![Diagram](image)

**Fig. 4** FDM wireless communication system. (a) Block diagram. (b) Photograph of experimental setup.
Fig. 5 The experimental results of the FDM wireless communication. 
(a) BER characteristics of low-frequency channel (300 GHz). 
(b) BER characteristics of high-frequency channel (335 GHz). 
(c) Eye diagrams.

5. Conclusion

We developed a 300-GHz-band silicon diplexer with integrated filters for FDM wireless communications. The diplexer includes a low-pass filter and a high-pass filter to suppress crosstalk. The low-pass filter is realized based on a one-dimensional photonic crystal structure with a bandgap tailored to the upper-end of the operation bandwidth. On the other hand, the high-pass filter is realized with a narrow-width waveguide bend that radiates low frequencies. With this design, the diplexer offers high isolation of above 15 dB with the frequency range of more than 30 GHz on each channel. We have also demonstrated 36-Gbit/s error-free wireless communications with FDM scheme using the diplexer on the receiver side. In a related work [16], it has also been shown that using the diplexer both on a transmitter side and a receiver side can increase system capacity to 48 Gbit/s, which proved to be sufficient for uncompressed 8K video transmission.

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References


