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# Near-field out-of-plane coupling between terahertz photonic crystal waveguides: supplementary material

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**This document provides supplementary information to "Near-field out-of-plane coupling between terahertz photonic crystal waveguides," https://doi.org/10.1364/OPTICA.6.001002. The results of several numerical simulations that support the arguments given in the main text are presented.**

## 1. IMPACT OF MISALIGNMENT

It is of interest to quantify the degree to which the performance of the out-of-plane coupler structure is degraded by misalignment in the $y$-direction. To this end, full-wave numerical simulations are performed using CST Microwave Studio that evaluate the transmission of the vertical coupler when there is a lateral spatial shift between the top and bottom waveguides. For these simulations, vertical separation is $d = 100$ µm, and overlap length is $L_{\text{overlap}} = 4$ mm.

Simulation results are presented in Fig S1. These results indicate that minor misalignment (i.e. less than 100 µm) produces a minor red-shift in the central frequency of the vertical coupler, but does not markedly impact maximum coupling efficiency. It is noted that, when compared with the simulation results given in Fig. 3(b) of the main text, this red-shift is similar to the impact of reducing $L_{\text{overlap}}$. This can be understood as the coupling effect being weakened, and hence a longer overlap length would be required to compensate. Thus, minor horizontal misalignment can be considered equivalent to increasing the vertical separation $d$; both reduce the evanescent interaction between the coupled lines. For larger misalignment (i.e. 150 µm and greater), evanescent interaction is reduced to the extent that significant loss is observed, and the vertical coupler essentially becomes unusable. That said, the fact that the samples are situated within a walled cavity, of width 100 µm greater than the samples themselves, places an upper limit on the lateral misalignment of the samples.

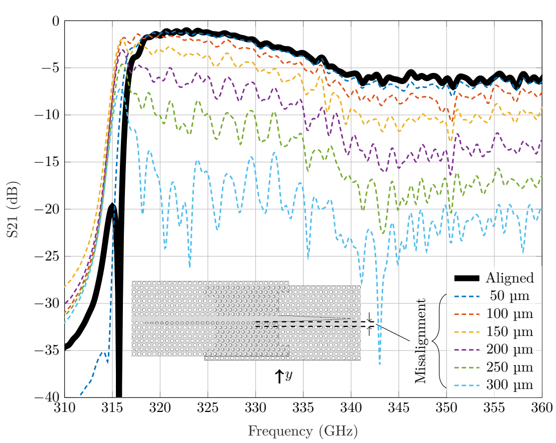


**Fig. S1.** The results of numerical simulations that probe the impact of horizontal misalignment. The physical situation under investigation is illustrated as inset.

Aside from $y$-direction misalignment, it is also of interest to know the impact of angular misalignment, i.e. if the planar samples are not perfectly aligned. To this end, simulations are performed in which one of the samples is rotated with respect to the other, around the $y$-axis. The pivot point of this rotation is the center-point of the coupled-line section, and only minor angles are tested in this way, so as to avoid a collision between the two waveguides. The results of these simulations are given in Fig. S2. As in the case of minor lateral misalignment, the centre frequency of the vertical coupling junction shifts slightly downward, and there is minimal impact upon overall efficiency. It is also noted that the given values of rotation angle are somewhat exaggerated, as the sample holder will prevent this degree of angular misalignment.

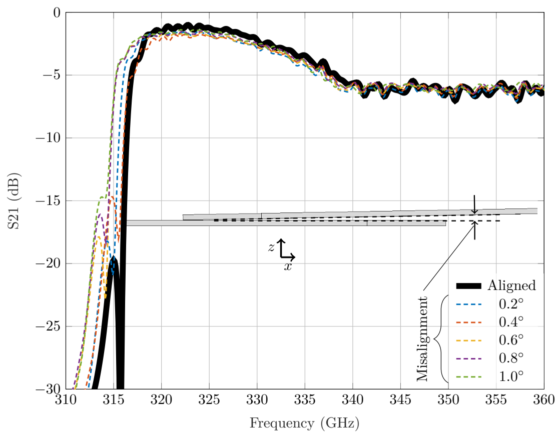


**Fig. S2.** Numerical simulations that investigate the impact of angular misalignment (i.e. rotation in the $xz$-plane) on the transmission efficiency of the vertical-coupling structure.

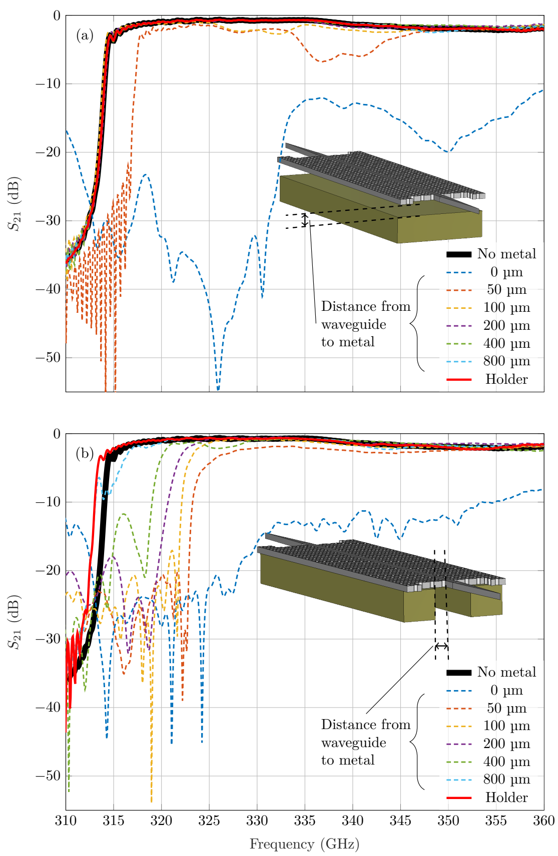


**Fig. S3.** Simulated interaction between terahertz photonic crystal waveguide and nearby metal, for (a) a metal block placed below the waveguide, in order to determine whether the sample holder's trench depth is sufficient, and (b) a bifurcated block of metal beneath, and in contact with the silicon, in order to determine whether the lateral separation between the waveguide and metal is sufficient. Both scenarios are illustrated as inset to the relevant plot.

## 2. INTERACTION BETWEEN WAVEGUIDE AND METAL HOLDER

Full-wave simulations are performed using CST Microwave Studio in order evaluate the impact of the metal sample holder

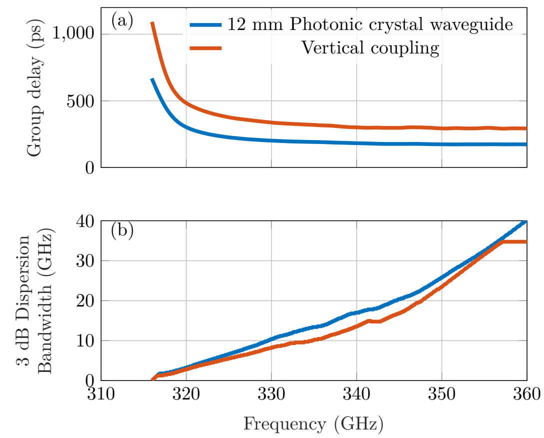


**Fig. S4.** An analysis of dispersion, showing (a) group delay, and (b) dispersion-limited 3 dB bandwidth, for a vertical coupling junction with $L_{\text{overlap}} = 4$ mm, and $d = 100$ µm, as well as a single straight section of terahertz photonic crystal waveguide.

upon the performance of the photonic crystal waveguide. The test case of a 1 cm-long terahertz photonic crystal waveguide is selected for this purpose, and blocks of PEC are employed to represent the metal. Simulation results are summarised in Fig. S3. The depth and width of the trench are investigated separately, in Fig. S3(a) and (b), respectively. It is noted that the geometric parameter that is given in the legend of Fig. S3(b) is not trench width, but the physical distance the separates the waveguide track from the metal, and this determines the width of the trench. The geometric parameters corresponding to the physically realized sample holder are included in the simulations.

It is clear from the results in Fig. S3 that the presence of metal only produces a pronounced negative impact when it is very close to the defect-row waveguide. For trench depth, the selected parameters of the realised sample holder yield transmission that is essentially indistinguishable from a waveguide in isolation. For the trench width, on the other hand, it appears that the presence of the metal lowers the waveguide's cutoff frequency by ∼1 GHz. The photonic crystal supports propagating modes below the cutoff of its photonic bandgap. Thus, it is likely that this minor frequency shift is due to radiation leaking from the waveguide into the photonic crystal, and subsequently being reflected from the metal back into the waveguide. It is noted that, above this cutoff frequency, the transmission is close to identical to the no-metal case. From these results, we can conclude that the sample holder's electromagnetic interaction with the photonic crystal waveguide is negligible within the waveguide's operation bandwidth.

## 3. NUMERICAL DISPERSION ANALYSIS

In the communications experiments that are presented in the main text, the achievable data rate was found to be limited by dispersion. For this reason, we deem it prudent to include an analysis of the impact of dispersion upon the vertical coupling structure. This consists of group delay, and the ensuing dispersion-limited bandwidth, which are calculated from the results of numerical simulations, and presented in Fig. S4. A straight section of terahertz photonic crystal waveguide is also included in this analysis, for comparison.

It is apparent from Fig. S4(b) that the vertical coupling junction's 3 dB bandwidth is consistently slightly lower than that of the straight waveguide. This indicates that, although the coupled-line structure is dispersive to a degree, the majority of the dispersion is contributed by the photonic crystal waveguide itself.

Fig. S4(b) shows that lower dispersion, and higher dispersion-limited bandwidth are available at frequencies in the vicinity of 360 GHz. Indeed, previous experiments have shown that the dispersion of the photonic crystal waveguide is markedly lower around 360 GHz [28], leading to higher data rates. However, propagation loss is significantly greater at such frequencies, due to the phenomenon of progressive leakage that is mentioned in Section 3 of the main text. It is stated in Section 1 that the high efficiency of terahertz photonic crystal waveguides is of crucial importance. For this reason, we have chosen to eschew such higher frequencies for this study, in order to concentrate our efforts upon the frequency band that exhibits high efficiency.