Silicon socket layer for highly tunable phonon-phonon coupling in integrated circuits

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Abstract: We investigate acoustic coupling between two silicon waveguides through a 60 nm-thin silicon “socket” layer. The coupling turns out to be highly dependent on the socket length. The structure holds promise for microwave processing.

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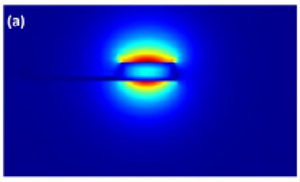
Stimulated Brillouin scattering was recently demonstrated on the silicon-on-insulator platform using partially suspended [1] and free-standing [2] silicon nanowires. These structures harnessed a good overlap between the quasi-TE polarized fundamental optical mode and a 10 GHz acoustic mode. The acoustic mode was essentially the fundamental Fabry-Pérot-like vibrational mode of the nanowire [1]. Here, we focus on quasi-TM polarized light (fig.a). Thus, we rotate both the optical and acoustic field by 90° (fig.b) with respect to the TE-based work [1, 2]. This allows for better power handling (lower two-photon absorption), and higher mechanical frequency (17.6 GHz instead of 9 GHz). Crucially, this rotated acoustic mode has a small displacement at the connection to the socket (fig.d). Therefore, it generates relatively weak coupling to the adjacent waveguide. This is important to realize a 2nd order radio-frequency filter response [3]. This small displacement also allows us to avoid the design of a phononic bandgap, in contrast to a previous silicon nitride structure [3]. Besides microwave filtering [3], using the socket layer as a phonon coupler may find use in integrated phonon networks [4, 5].

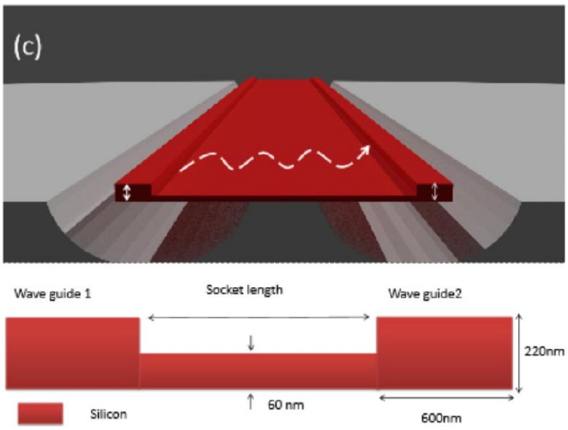
Our design is composed of two 600 nm × 220 nm silicon waveguides (WG-1 and WG-2) connected by the 60 nm-thin socket layer (Fig. c). This socket layer can be fabricated in standard silicon photonics fabs (`www.europractice-ic.com/`). We simulated both the photon-phonon (of a single waveguide) and the phonon-phonon coupling (between the waveguides) with the finite-element solver COMSOL. The acoustic coupling generates a symmetric and anti-symmetric acoustic mode, whose difference in frequency is μ. The socket length offers a large tunability in coupling rate μ: from 0 MHz to 36 MHz given only a 100 nm change in socket length (fig.e). This shows, for the first time, how a thin silicon layer can be used to phononically couple silicon waveguides – and in a highly versatile manner. Besides its potential in microwave photonics [3], this layer could be used more generally, e.g. to couple out phonons from an on-chip mechanical laser into a phononic bus waveguide [6]. The physics of the coupler will be analyzed in detail elsewhere. Notably, this phonon-phonon coupler is not evanescent. In particular, this coupling does not decrease monotonically (fig.e).

The tunability allows us to match the coupling rate μ to the mechanical loss rate κ of our oscillator for a large range of mechanical quality factors: from 500 to more than a million. This matching condition allow us to maximize phonon-mediated information transfer between the two waveguides. The cross-phase modulation efficiency is directly related to the Brillouin gain coefficient in a single waveguide [3]. The Brillouin interaction is dominated by the boundary nonlinearity, unlike before [1, 2]. Assuming a mechanical Q of 1000, we simulate reasonable efficiencies of about $1000\,\mathrm{m}^{-1}\mathrm{W}^{-1}$. Therefore, there is little doubt that this phonon-phonon coupling method can indeed be measured via Brillouin scattering.

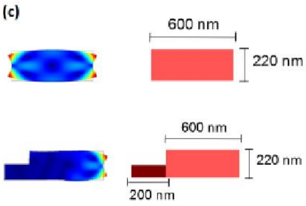


(a) Electric field norm of the quasi-TM optical mode.

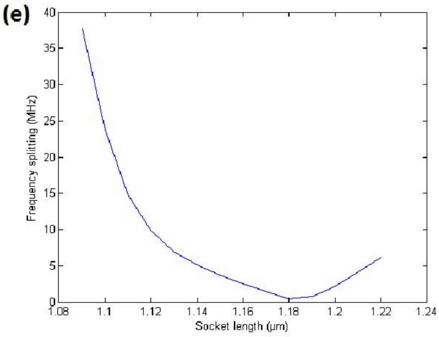
(b) The phonons are trapped transversely in the waveguide.



(c) Two silicon waveguides that are acoustically coupled through a thin silicon layer. Solid arrows represent trapped phonons bouncing up and down. Dashed arrows show the vibrational excitation of the socket, which mediates the coupling.



(d) Displacement field of the acoustic mode of the fundamental Fabry-Pérot-like vibrational mode with (bottom) and without (top) a connection to a socket.



(e) The acoustic mode splitting strongly depends on the socket length.

In conclusion, our analysis demonstrates that nanoscale silicon waveguides can be coupled acoustically in a highly tunable manner via a thin silicon socket layer. We expect experimental results in the coming months.

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