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Metasurface Oligonucleotide Synthesizer for Genetically Engineered Biology

Stanford researchers have developed an innovative metasurface-enabled, CMOS-compatible platform for high-density, on-chip oligonucleotide synthesis that enables precise, site-selective DNA production without mechanical scanning or complex photolithographic alignment.

The platform uses optically addressable dielectric nanoantenna arrays integrated with localized thermal actuation and microfluidics to perform programmable oligonucleotide synthesis directly on chip. The technology addresses key limitations of existing oligonucleotide synthesis platforms, including restricted synthesis density, alignment errors, limited scalability, and high chemical waste. Conventional photolithographic and inkjet-based approaches rely on moving parts, physical masks, or repeated alignment steps that constrain throughput and increase error rates as synthesis density scales. In contrast, this platform enables spectral and polarization-based optical addressing, allowing individual synthesis sites to be selectively activated without physical reconfiguration or mechanical motion.

The system integrates high-Q dielectric nanoantennas coupled to plasmonic nanostructures that provide tightly confined, localized heating for site-specific thermolytic deblocking, followed by enzymatic nucleotide coupling within an aqueous microfluidic environment. This architecture supports ultra-high synthesis densities (on the order of millions of sites per square centimeter) while maintaining strong site isolation and minimizing cross-talk.

By combining metasurface photonics, enzymatic chemistry, and CMOS-compatible fabrication, this technology enables scalable, reconfigurable, and environmentally sustainable DNA synthesis, supporting applications that require large, diverse oligonucleotide libraries with improved fidelity and manufacturability.

Applications

- High-throughput oligonucleotide synthesis for synthetic biology and genetic research
- Diagnostics and DNA-based biosensors (e.g., aptamers)
- Vaccine, therapeutic, and drug development
- DNA data storage and advanced bio-enabled materials

Advantages

- Ultra-high synthesis density with millions of addressable sites per chip
- Reduced synthesis errors through non-mechanical, optical site selection
- Reconfigurable operation via wavelength and polarization control
- Environmentally friendly, enzyme-based aqueous chemistry
- CMOS-compatible fabrication enabling scalable and cost-effective manufacturing

Publications

- Padhy, P., Zaman, M. A., & Dionne, J. Temperature bandgaps and thermal dopants arising from photothermal nonlinearities in high-Q silicon metasurfaces. preprint arXiv:2511.12038.

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