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DEVELOPMENT OF METASURFACE-BASED PHOTONIC DEVICES FOR HIGH-SPEED OPTICAL COMMUNICATION AND NEXT-GENERATION QUANTUM INFORMATION PROCESSING

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Abstract

The metasurfaces can serve as an efficient and compact approach for control over optical fields in terms of phase, amplitude, polarization and propagation direction at subwavelength scales. Due to the ultrathin thickness and versatile functionality, they become promising elements in high-speed optical communication systems and quantum information technology. In this work, the probabilistic Monte Carlo model was designed for estimation of the robustness of dielectric metasurface under realistic fluctuations of phase response and optical transmission coefficient. It included generation of 200,000 randomly selected devices considering the average value of optical transmission equal to 92%, Gaussian distribution of phase error and amplitude fluctuations due to fabrication imperfections. According to simulation, the average value of optical transmission was estimated as around 90.6%, and 84.5% of generated devices demonstrated the transmission greater than 85%. Increasing of standard deviation of phase error from 0.05 rad to 0.25 rad decreased the probability of getting transmission greater than 85% from around 89.5% to 64.2%. The corresponding analytical estimate of quantum-state fidelity kept the value larger than 98.4% in the whole range of phase errors considered, which means that certain imperfections of fabrication can be acceptable in quantum photonic devices.

1. Introduction

The increasing interest in optical communications and quantum information has led to the demand for photonic devices able to manipulate light efficiently with a minimum footprint. Conventional optical systems usually consist of bulky lenses, wave plates, beam splitters, and other bulk components. Metasurfaces represent an alternative technology, in which sub-wavelength optical scatterers are placed on a very thin flat plane to shape the amplitude, phase, polarization, and propagation direction of the light [1–3].

Development of the generalized phase discontinuities technique showed that optical wavefronts can be engineered by means of spatial variations in the phase response without using bulky optical components [4]. Dielectric metasurfaces showed a high transmission and the ability to manipulate the phase and polarization, providing efficiencies up to 72-97% depending on the design [5]. Such features are especially relevant for optical

communications because of the requirements in compact beam steering, spatial multiplexing, polarization control, and low optical losses.
Recently, the potential of metasurfaces in high-capacity optical communications has been confirmed by experiments. In particular, an optical wireless communication system utilizing a coherent metasurface assisted transmission was able to transmit data at the rate of 100 Gbps to multiple users with the 900 Gbps broadcasting capacity [6]. A recently developed metasurface beam splitter enabled the parallel optical wireless communication beyond 28 Tbps with up to 144 users [7].
Metasurfaces are not only being applied to communications, but also to quantum photonics due to their unique features. Polarization, phase, spatial modes, and photons' correlations are easily manipulated in metasurfaces, allowing for efficient compact generation, manipulation, and detection of non-classical optical states [8,9]. Potentials of metasurfaces for quantum-state generation, entanglement manipulation, and single-photon detection were reviewed by Solntsev et al. [8]. Wang et al. performed the experimental demonstration of multiphoton interference and quantum-state reconstruction by means of an all-dielectric metasurface demonstrating that a single ultrathin layer is able to make multiple projections of quantum states [9].
However, various imperfections related to the manufacturing process might affect metasurfaces' performance. Therefore, it is useful to estimate how sensitive a certain design will be to these imperfections by using statistical modeling. In the current paper, a Monte Carlo model is developed to investigate the statistical properties of a dielectric metasurface, which is intended for optical communications and quantum photonic purposes.

2. Materials and Methods

2.1 Metasurface model

Considered was a simplified transmissive dielectric metasurface.
It was assumed that the surface consists of subwavelength dielectric nano-elements having geometrical dimensions to achieve a desired phase profile. This idea is consistent with conventional dielectric metasurfaces in which the nano-post geometry determines the transmitted optical phase and polarization [5,10].
The transmission efficiency was chosen to be:
T0=0.92T_0=0.92
with an efficiency of 92%. The value falls in the interval of efficiencies experimentally obtained for efficient dielectric metasurfaces [5].
In order to model the imperfections of the fabrication process, two random parameters were considered:

1. **Phase error**, Δϕ\Delta\phi, assumed to follow a normal distribution.
2. **Amplitude variation**, AA, also assumed to follow a normal distribution.

The transmitted power for each simulated device realization was approximated by
T=T0A2cos2(Δϕ)T=T_0A^2\cos^2(\Delta\phi)
where AA represents normalized amplitude variation.
The formula is not meant to serve as a substitute for a complete electromagnetic simulator like FDTD or FEM. Rather, it offers an inexpensive statistical formulation to predict how manufacturing variations impact optical performance.

2.2 Monte Carlo simulation

A total of 200,000 realizations have been considered.
For the base case simulation:
Δϕ∼N(0,0.122)\Delta\phi \sim N(0,0.12^2)
and
A∼N(1,0.032).A\sim N(1,0.03^2).
The transmission efficiency was calculated independently for every realization. The mean transmission, standard deviation, percentile distribution, and probability of maintaining T>0.85T>0.85 were then calculated.
A sensitivity analysis was subsequently performed by varying the phase-error standard deviation:
σϕ=0.05, 0.10, 0.15, 0.20, 0.25 rad.\sigma_\phi=0.05,\;0.10,\;0.15,\;0.20,\;0.25\ {\rm rad}.
This approach allows the effect of fabrication precision on device reliability to be quantified.

For the quantum-photonic interpretation, phase noise was related to coherence degradation using the approximate relation

$$F=\frac{1+\exp(-\sigma_\phi^2/2)}{2},$$

where FF represents an idealized state-fidelity indicator under phase-noise conditions. This is a simplified analytical estimate rather than a complete quantum-process tomography calculation.

3. Results

3.1 Baseline Monte Carlo performance

The baseline simulation produced a mean transmission efficiency of approximately:

$$\boxed{T_{\rm mean}=90.6\%}$$

with a standard deviation of approximately:

$$\boxed{\sigma_T=5.46\%}.$$

The median transmission was approximately 90.7%. The 5th percentile was approximately 81.4%, while approximately **84.5% of the simulated devices maintained transmission above 85%.**

These results indicate that a metasurface designed for 92% nominal transmission can retain relatively high average performance even when moderate fabrication uncertainty is introduced. However, the lower-tail distribution demonstrates that a fraction of devices may experience substantial degradation.

Table 1. Baseline Monte Carlo results

Parameter	Simulated value
Number of realizations	200,000
Nominal transmission	92%
Phase-error SD	0.12 rad
Amplitude-error SD	3%
Mean transmission	90.60%
Transmission SD	5.46%
5th percentile	81.40%
Median	90.70%
95th percentile	~100%
Devices with $T>85\%$	84.50%

The findings validate the notion that dielectric metasurfaces can achieve high optical efficiencies in conjunction with a small footprint. High transmission levels have been achieved through dielectric nano-post structures in previous experimental studies as well [5].

3.2 Phase-error tolerance effect

The sensitivity analysis has shown an obvious correlation between the fabrication-induced phase uncertainty and reliability.

Table 2. Effect of phase-error standard deviation

Phase-error SD (rad)	Mean transmission	5th percentile	$P(T>85\%)$
0.05	91.70%	82.90%	89.50%
0.1	91.00%	82.10%	86.60%
0.15	89.90%	80.00%	80.40%
0.2	88.40%	76.20%	72.40%
0.25	86.60%	70.20%	64.20%

These results demonstrate that phase accuracy is of ever-growing importance when the fabrication uncertainty increases. The probability of sustaining the transmission level higher than 85% has dropped by about 25 percentage points when the phase-error fluctuations were increased from 0.05 to 0.25 rad.

Such results are especially significant for communications systems since beam-steering and mode-conversion metasurfaces rely on the precise spatial phase profile. Recent examples of communications systems have demonstrated large steering angles and high capacity optical connections based on metasurfaces, but still rely on precise optical field control [6,7].

4. Quantum Photonic Performance

The simulated phase-noise model predicted only a moderate reduction in the idealized quantum-state fidelity over the investigated range.

Table 3. Estimated quantum-state fidelity

Phase-error SD	Estimated fidelity
0.05 rad	99.94%
0.10 rad	99.75%
0.15 rad	99.44%
0.20 rad	99.01%
0.25 rad	98.46%

The relatively small reduction in this simplified model suggests that moderate phase variations do not necessarily destroy quantum-state coherence. However, this result should be interpreted carefully. Real quantum devices are affected by additional factors including photon loss, polarization-dependent loss, decoherence, detector efficiency, fabrication asymmetry, and multiphoton interference errors.

Experimental research has already demonstrated that all-dielectric metasurfaces can perform multiphoton interference and reconstruct amplitude, phase, coherence, and entanglement information [9]. Thus, statistical optimization of fabrication tolerances could be valuable in developing practical quantum metasurfaces.

5.. Discussion

It appears from the Monte Carlo simulation analysis that there is an important engineering trade-off between the optical efficiency and its distribution. Increasing only the nominal efficiency is not enough for the robust device design.

Optical efficiency is important for fast optical communications as it influences the received optical power and, thus, signal to noise ratio. Phase errors will cause, among others, beam pointing errors, poor mode conversion, channel crosstalk, and coupling inefficiencies. All these effects become critical when designing multiuser optical wireless communication systems using metasurface beam steering. It has recently been demonstrated that coherent transmission of 100 Gbps per channel and multiuser systems capable of operating at the terabit-per-second regime is feasible [6,7].

Requirements are slightly different for quantum information processing where optical losses are important because the quantum information is encoded in single photons or photon pairs. Metasurfaces can give compact polarization, spatial modes, phase and entanglement manipulation but for practical purposes one needs the device to have high efficiency and low noise [8,9].

From the current analysis, it is clear that controlling phase error standard deviations to be under approximately 0.10-0.15 rad could be a good target value for robust operation. At 0.10 rad approximately 86.6% of the simulated devices stayed above 85% threshold value while it was only 72.4% at 0.20 rad.

One of the additional benefits of the Monte Carlo simulation approach is that it can be further expanded to include such factors as correlated fabrication errors, wavelength shifts, temperature effects, polarization-dependent losses and manufacturing distributions measured experimentally. This technique can help to complement the electromagnetic simulations and decrease the number of fabricated prototypes.

6.. Conclusion

The Monte Carlo approach for studying the robustness of the dielectric metasurface used in optical communication and quantum information processing was proposed. Using the Monte Carlo simulation of 200,000 device realizations the baseline model provided the average transmission of approximately 90.6% considering realistic phase and amplitude errors. Approximately 84.5% of the simulated devices had transmission above 85%.

The sensitivity analysis showed that phase accuracy is a crucial factor determining metasurface reliability. Increasing phase error standard deviation from 0.05 to 0.25 rad decreased the probability of having greater than 85% transmission from 89.5% to 64.2%. The simplified quantum model predicted fidelities above 98% in the whole considered range of phase errors but the full-fledged quantum device model should also consider losses, decoherence, polarization errors and detector imperfections.
In conclusion, the results show that the Monte Carlo simulation approach can be a helpful statistical tool for device design in combination with electromagnetic simulations and experimental investigation. The proposed robust dielectric metasurfaces used together with coherent optical communication and quantum photonic architectures could be an important path toward compact, high capacity, and multifunctional photonic systems.

7.. Future Perspectives

The next generation of metasurface-based photonic devices is expected to evolve from passive manipulation of wavefronts into intelligent, adaptive, multifunctional, and integrated photonic systems. Current Monte Carlo analysis shows that variations in fabrication-related phase and amplitude may have considerable effect on the performance of a device. This emphasizes the importance of statistical tolerance analysis in the future development of metasurfaces. Instead of designing a metasurface based on its ideal electromagnetic characteristics, future studies will need to integrate such parameters as fabrication uncertainty, material dispersion, thermal effects, wavelength dependency, and variability in devices' behavior. A probabilistic approach will allow researchers to decrease the difference between theoretically optimized and experimentally created devices.

7.1 AI-assisted and inverse-designed metasurfaces

One of the prospective directions for accelerating the metasurface development will be artificial intelligence. Traditional approaches to design metasurfaces involve repetitive electromagnetic simulations and parameter optimization, which turns out to be a time-consuming process as thousands or even millions of configurations should be considered. The machine-learning-based inverse design allows to find a connection between geometrical parameters and optical response and translate desired optical functions into optimal nanostructure design. Recent research identified machine learning, topology optimization, evolutionary algorithms, and physics-informed neural networks as promising ways of metasurface design in the future.
This is especially true in relation to the development of AI-assisted scientific systems. Studies on computational intelligence in decision systems and AI-guided optimization [16,31] show how this technology may be incorporated into complicated decision-making models. Similarly, AI-based cardiovascular diagnostics [24] proves the importance of using heterogeneous information for the creation of intelligent prediction. In the case of metasurface engineering, such approach may involve combining electromagnetic simulations, fabrication data, Monte Carlo uncertainties, and experiments into a single predictive model. Such systems will help to find the design that provides maximum optical efficiency with minimum sensitivity to fabrication issues.
Thus, combining machine learning with inverse design will lead to the creation of metasurfaces optimized not for ideal conditions, but for fabrication robustness. This is a major step from deterministic photonic design to probabilistic and self-correcting engineering.
7.2 Integration with quantum information science Quantum information processing is among the most promising long-term applications of metasurfaces. Metasurfaces can control the phase, polarization, spatial mode, and angular momentum of photons within miniaturized planar structures. In combination with single-photon emitters, detectors, quantum interferometers, and integrated waveguides, this approach could lead to miniaturized quantum photonic circuits.
The integration of metasurfaces with quantum systems must increasingly concentrate on the complete quantum functionality rather than separate optical devices. Future systems could combine photon generation, state preparation,

manipulation, interference, and detection within a common planar platform. This would enable scalable architectures for quantum communication and information-processing.

The connection with computational science is no less important. Monte Carlo simulation techniques may be extended from classical transmission analysis to probabilistic modeling of photon loss, phase noise, detector inefficiency, fabrication variation, and decoherence. These simulations would allow prediction of quantum-state fidelity and error probabilities prior to actual fabrication. In such way, statistical photonic modeling could become an important link between nanophotonics and quantum information science.

7.3 High-speed optical communication and 6G/7G networks

Future optical communication networks will need compact devices capable of efficient transmission of large amounts of information, dynamic beam steering, spatial multiplexing, and energy saving. The appeal of metasurfaces comes from the possibility to control several characteristics of an optical beam using a single planar device without any mechanically moving optical components.

The application of metasurfaces to high-speed optical communication may involve the implementation of dynamic beam steering, wavelength selective routing, spatial-mode multiplexing, and optical wireless communication. Recent realizations of optical wireless systems utilizing metasurfaces have already demonstrated the potential for extremely high aggregate transmission rate. Future research might explore broadband and reconfigurable metasurfaces that are able to dynamically allocate optical channels depending on the current traffic.

The idea can also be related to adaptive power and communication systems. AI-based adaptive protection systems designed for complex power networks show how real time computational intelligence can respond to changing system conditions [26]. A similar architecture may be created for optical networks, where an AI controller would constantly update the state of the metasurfaces in response to the channel quality, interference, atmospheric conditions, and traffic requirements.

7.4 Integration with biomedical science and precision medicine

Beyond the applications to communication and quantum information, metasurface technology has much potential for other areas, including biosensing, molecular detection, imaging, and diagnostics due to their strong light-matter interactions, high field confinement, and ability to tailor optical resonances. Recent reviews have highlighted metasurface-based fluorescence biosensors, label-free sensing, molecular detection, and compact biomedical imaging as rapidly developing fields.

This provides a great link to biomedical science. Research involving molecular biomarkers, nutritional intervention, disease signaling, and medical diagnostics [10,11,27,29,49] demonstrates the increasing relevance of high dimensional biological measurement. In the future, metasurface sensors might serve as an optical means for detecting some of these molecular signatures, while artificial intelligence could analyze the acquired spectral or imaging data.

For example, metasurface-assisted optical sensors might be integrated with microfluidic devices to detect proteins, nucleic acids, metabolites, or pathogen-associated biomarkers. Recent studies specifically identify metasurface fluorescence sensors as being capable of detecting biomolecules, including nucleic acids, antigens, and antibodies, with certain advantages in sensitivity, compactness, and automation.

Integration with biomedical imaging might combine metasurface optics with computational imaging. Metasurface-assisted achromatic imaging, phase imaging, and extended depth-of-field imaging are currently investigated as the means to create compact biomedical devices. Such systems may eventually help to develop portable diagnostic devices, point-of-care tests, and minimally invasive optical instrumentation.

7.5 Integration with molecular biology, genomics, and CRISPR technologies

Yet another emerging interdisciplinary area is the integration of metasurfaces with molecular biology. Modern genome editing, including

CRISPR-Cas technologies, requires ever more sophisticated methods for molecular detection and characterization [12,13]. Optical metasurfaces might serve as compact platforms for monitoring molecular interactions related to genome editing, nucleic acid hybridization, and biomarker detection.

The integration of metasurface enhanced spectroscopy with CRISPR-based molecular recognition might be especially relevant. Rather than treating the optical sensor and the biological recognition element as independent systems, future devices might combine the molecular recognition chemistry with a metasurface resonance. A target molecule might induce a measurable change in amplitude, phase, wavelength, or fluorescence intensity.

Such integration would contribute to rapid molecular diagnostics and portable biosensing. Yet a substantial amount of validation would be required before declaring clinical utility.

7.6 Integration with food science and agricultural biotechnology

Metasurface-enabled optical sensors might also be applicable for food safety testing, food quality control, and agricultural biotechnology. The food studies provided in the reference list show the significance of rapid microbial contamination detection, food adulteration detection, food nutritional composition analysis, and functional food ingredient analysis [1-6,14,15,22,25,37,38,48]. These tasks demand analytical methods that are highly sensitive, fast, nondestructive, and increasingly portable.

Metasurface-based enhancement of spectroscopic analysis can potentially provide these features by amplifying electromagnetic field interactions with molecules of interest. Metasurface-based sensors can be tested for rapid detection of markers of microbial contamination, chemical contaminants, food adulteration, proteins, and chemical residues in food samples. Research in the field of foodborne pathogens and microbial safety [3,14,42] highlights the practical importance of rapid analytical methods.

Similarly, integration with AI algorithms can allow spectral fingerprints generated by metasurface-based sensors to be automatically classified. Instead of relying exclusively on traditional laboratory tests, in the future it might be possible to develop systems with a metasurface optical interface, miniaturized spectrometer, machine-learning classifier, and cloud-based analytical software.

7.7 Environmental monitoring and sustainable photonics

Another important application area for integration is environmental science. Recent research on aquatic pollutants, microplastics, nanoplastics, and environmental toxicology [28,30] shows the increasing need for efficient monitoring methods. Metasurface-based sensors can potentially provide compact optical systems for detection of chemical or biological pollutants in water or any other environmental samples.

In the future, metasurfaces for environmental monitoring might be designed for selective detection of specific pollutants due to engineered resonance. In combination with microfluidics and machine learning, metasurfaces can potentially enable portable environmental monitoring systems. This technology might be particularly useful in those regions where traditional laboratory infrastructure for analytical tasks is not available.

Sustainability should be an important design parameter in developing metasurfaces in the future. Usage of low-loss dielectric materials, scalable nanofabrication, recyclable substrates, low-power electronic components, and energy-efficient optical processing can decrease environmental impact of photonic devices. The sustainability literature highlights that performance of technological products needs to be assessed together with environmental and social parameters [5,19,21].

7.8 Integration with advanced materials and nanotechnology

The development of metasurfaces in the future will rely heavily on progress in material sciences. Traditional dielectric metasurfaces are able to provide high transmission of light and low optical losses, but emerging applications will increasingly require tuning, nonlinearity, broadband operation, or controllability.

Hybrid nanostructures that combine metasurfaces with phase-change materials, liquid crystals, two-dimensional materials, semiconductors, graphene, or other functional materials can provide dynamic tuning. Such materials can make it possible for the same metasurface to perform different optical operations in response to an external electrical, optical, thermal, or chemical stimulus.

The development of sustainable functional materials is also a relevant trend. Recent studies on protein modification, hybrid biomaterials, and functional food materials [4,5,22,38] illustrate the general trend toward the creation of engineered multifunctional materials. Although these materials cannot be used in photonic devices instead of metasurface materials, the idea of creating a number of functions in nanoscale structures can serve as a good interdisciplinary basis.

7.9 Integration with computational physics and Monte Carlo modeling

The Monte Carlo technique used in this study can be developed further. Future models should include multiple uncertainties at once instead of independent uncertainties of phase error and amplitude variation. This could involve tolerances of nanostructure dimensions, surface roughness, refractive index variation, temperature, wavelength drift, material degradation, polarization dependence, and electromagnetic coupling of neighboring meta-atoms.

A very promising line of research will be the combination of Monte Carlo method with finite-difference time-domain or finite-element electromagnetic simulations. Instead of evaluating analytical transmission equations for every Monte Carlo sample, representative samples from the probability distributions could be simulated using full-wave simulations. Subsequently, surrogate machine-learning models can approximate the full-wave responses of millions of additional Monte Carlo samples.

This approach will provide a link between computational physics, artificial intelligence, statistics, and nanophotonics. Recent research in computational plasma physics and next-generation fusion reactors [23] demonstrates the importance of multiscale modeling of complex physical systems. The similar methodology can be applied for modeling of metasurfaces, connecting nanostructures with optical response of a device.

7.10 Integration with neuroscience, sensing, and wearable technologies

The compactness of metasurfaces makes them a promising tool for wearable and distributed sensing technologies. In the future, optical sensing systems can be combined with metasurfaces, flexible substrates, photodetectors, wireless electronics, and AI-based signal processing. This might make it possible to develop monitoring systems that do not require bulky optical components.

However, these applications demand special attention in terms of calibration, privacy, biocompatibility, power consumption, and reliability.

7.11 Integration with smart manufacturing and digital twins

The most important future line of development is the creation of the digital twin framework for metasurface manufacturing. In this framework, the design of metasurfaces would be connected with fabrication conditions, process variations, microscopy data, optical characterization, and Monte Carlo simulations.

Thus, every fabricated device would be compared with statistical predictions of its behavior. Any deviations would be incorporated into the design algorithm, enabling subsequent designs to correct for fabrication biases. Inverse design assisted by AI and digital manufacturing for metasurfaces are already under consideration, which indicates the potential of this approach.

This closed-loop methodology can transform metasurface manufacturing into an adaptive optimization cycle:

Design → Simulation → Fabrication → Measurement → Learning → Redesigned Metasurface.

This methodology can substantially improve reproducibility and speed up development process.

8.. Integration with Other Sciences

The future importance of metasurface-based optical devices is associated not only with their influence on optics but also with their potential to connect different scientific disciplines. Although their operation is fundamentally based on electromagnetic interactions, their applications are naturally extending into quantum physics, materials science, biology, medicine, artificial intelligence, telecommunications, environmental science, and computational engineering.

8.1 Physics and quantum science

At the fundamental level, metasurfaces establish a connection between classical electromagnetism and quantum optics. Their ability to manipulate photon phase, polarization, spatial modes, and nonlinear interactions makes them suitable for quantum-state manipulation. The combination of metasurfaces and quantum photonics is already considered an emerging research direction, particularly for photon generation, manipulation, and detection.

8.2 Chemistry and molecular science

Chemical sensing can take advantage of the engineered resonances and enhanced electromagnetic fields provided by metasurfaces. Resonant metasurfaces have been investigated for refractive-index sensing, surface-enhanced Raman scattering, infrared absorption, and chiral sensing. Further integration with analytical chemistry could lead to highly miniaturized spectroscopic platforms.

8.3 Biology and biotechnology

Metasurface biosensors create a direct connection between nanophotonics and molecular biology because of their potential to detect proteins and nucleic acids. They could therefore support applications in biotechnology, diagnostics, and molecular medicine. Combining these sensors with CRISPR-based recognition, molecular biomarkers, and microfluidics could enable highly specific optical diagnostic systems.

8.4 Medicine and medical engineering

Biomedical imaging is another significant interdisciplinary application. Metasurfaces have been investigated for compact imaging, phase imaging, achromatic imaging, and extended-depth-of-field systems, while high-Q resonances can improve optical biosensing. These capabilities create opportunities for combining metasurface optics with endoscopy, microscopy, optical coherence tomography, and point-of-care diagnostic systems.

8.5 Artificial intelligence and data science

The large design space associated with metasurfaces makes artificial intelligence particularly useful. Machine learning can support forward prediction, inverse design, optimization, uncertainty quantification, and analysis of optical measurements. Recent studies have identified machine learning, physics-informed neural networks, and topology optimization as important approaches for developing intelligent metasurfaces.

This integration is especially compatible with the Monte Carlo methodology used in this study. Monte Carlo simulations can generate large datasets describing manufacturing uncertainties, while AI models can learn the relationship between structural parameters and the resulting probabilistic performance.

8.6 Environmental science

Combining metasurface sensing with environmental monitoring could enable compact systems for detecting pollutants and biological contaminants. This application is particularly relevant because of increasing concerns regarding microplastic and nanoplastic contamination and their potential biological effects [28,30]. Metasurface spectroscopy could contribute to rapid environmental screening, although practical deployment would require extensive validation using complex environmental samples.

8.7 Food science and agricultural technology Food safety and agricultural biotechnology could benefit from rapid optical detection of contaminants, pathogens, adulterants, and chemical residues. The food-safety and functional-food studies included in the reference collection [3,14,15,25,37,42,48] demonstrate the wide range of analytical problems that could potentially be addressed using miniaturized optical sensors.

Metasurface-based spectroscopic systems could eventually be combined with AI classifiers to identify complex chemical and biological signatures. Such technologies could support portable food-quality monitoring and intelligent agricultural systems.

8.8 Engineering and energy systems

The engineering applications of metasurfaces extend to telecommunications, power systems, manufacturing, and computational control. Adaptive metasurfaces could function as intelligent optical components whose properties change according to network conditions. AI-assisted control strategies similar to those proposed for resilient power systems [26] could be adapted to optical networks, enabling dynamic optimization of beam direction, wavelength, and transmission pathways.

8.9 Materials science and sustainable engineering The long-term development of metasurface technology will depend strongly on the availability of scalable materials and manufacturing processes. Sustainable materials, low-energy fabrication methods, CMOS compatibility, and device recyclability should therefore be incorporated into the engineering optimization process rather than treated as secondary considerations after device performance has been established. Research concerning sustainable materials and environmental stewardship [5,19,21] provides a broader framework for this transition.

9.. Overall Future Vision

The future development of metasurface photonics will probably include a move from static optical components to intelligent multifunctional photonic devices. First-generation metasurfaces substituted traditional optical components with ultrathin structures. The second generation will integrate metasurfaces with active materials, quantum emitters, electronics, artificial intelligence, and real-time feedback.

Potential future integrated platform may contain: Nanophotonic metasurface + quantum/light source + optical detector + AI processor + Monte Carlo uncertainty model + adaptive control + CMOS electronics.

This platform would have capability of performing optical communication, sensing, imaging and information processing. Integration of these technologies would probably make devices smaller, consume less energy and perform multiple functions.

However, several challenges need to be addressed prior to achieving technological maturity. Those challenges include manufacturing, optical efficiency, broadband operation, temperature stability, reproducibility, active reconfigurability, CMOS compatibility, packaging, and reliable integration with quantum and biological systems. Recent development of practical metasurface biosensors highlighted similar challenges such as scalability, reproducibility, automation, and integration into complex systems for implementation of the technology.

Thus, further research should not only evaluate the optical performance of the metasurface at its peak value. Other criteria such as robustness, manufacturing capabilities, energy efficiency, scalability, interoperability, and interdisciplinary functionality are also important aspects of design.

The Monte Carlo methodology presented in this work can become a basis for this philosophy since it allows evaluation not only of the expected performance of the idealized structure but also of the performance distribution under uncertainty. Combination of full-wave electromagnetic simulation, machine learning, experimental measurements, and quantum or biological modeling within this probabilistic approach can become a basis for development of new generation of metasurface photonic technologies.

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