



Optically controlled metasurface antennas [Invited]

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Abstract: Over the past decade, metasurfaces (MTSs) have emerged as a highly promising platform for the development of next-generation, miniaturized, planar devices across a wide spectrum of microwave frequencies. Among their various applications, MTS-based antennas—particularly those based on surface-wave excitation—represent a significant advancement for communication technologies. In this paper, we report an experimental demonstration of an optically controlled Ka-band metasurface antenna realized by printing subwavelength metallic elements on a high-resistivity silicon substrate. By exploiting the photoconductive properties of silicon under near-infrared illumination, the complex permittivity of the substrate is locally modified, resulting in a change of the effective surface reactance. This mechanism enables optical control of surface-wave propagation and its conversion into radiation. Experimental results demonstrate optical control of the antenna radiation characteristics, with a measured gain variation of approximately 6.7 dB, while full-wave simulations of the fully silicon-based antenna configuration predict gain variations of up to 15 dB, under low optical power densities (below 1 W/cm² at 971 nm). Building on these results, we then propose and numerically validate a novel antenna concept in which the radiating functionality is entirely implemented in silicon, without any printed metallic elements. In this configuration, the metasurface behavior is achieved purely through spatial and temporal modulation of the substrate properties induced by optical illumination. Full-wave simulations demonstrate that this approach enables dynamic control of radiation characteristics, opening the way to fully photonic, reconfigurable microwave antennas. These results establish a new paradigm in antenna design, where optical excitation of a photosensitive substrate enables direct and efficient control of microwave radiation without the need for electronic tuning components or patterned conductive layers.

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1. Introduction

Metasurfaces (MTSs) are artificial, ultra-thin, two-dimensional structures composed of subwavelength unit cells, engineered to control the interaction between electromagnetic (EM) waves and matter. By properly designing the geometry and arrangement of these elements, metasurfaces enable a wide range of functionalities, including anomalous reflection and refraction [1–6], polarization conversion [7,8], and beam shaping or splitting [9,10].

In the microwave regime, metasurfaces are typically implemented using printed circuit board (PCB) technology, where electrically small metallic elements are patterned on a dielectric substrate [11]. Within this framework, the electromagnetic response of the metasurface is governed by an equivalent surface impedance, determined by the geometry of the printed elements and by the properties of the supporting substrate. Among the various applications, metasurface-based antennas—especially those relying on surface-wave (SW) excitation and

controlled leakage—have attracted significant attention due to their high efficiency, low profile, and flexible radiation pattern synthesis [12–26].

Recent research efforts have focused on introducing reconfigurability into metasurface antennas, typically by integrating electronic components or by modifying the substrate properties through external stimuli. In this context, photosensitive materials such as silicon offer an attractive opportunity, since their complex permittivity can be dynamically controlled through optical illumination. The photoconductive effect in silicon leads to the generation of free carriers, which locally modify the conductivity and, consequently, the effective electromagnetic parameters of the substrate. In this context, recently proposed all-dielectric approaches at terahertz frequencies have demonstrated reconfigurable wavefront manipulation using cascaded all-silicon metasurfaces, where the relative rotation between dielectric layers enables functionalities such as spin-dependent wavefront control, tunable focusing, and polarization-multiplexed beam steering [27,28]. Differently from the strategy of mechanically reconfiguring the architecture, the approach investigated here relies on spatially controlled optical generation of carriers to modify the electromagnetic properties of the silicon substrate, with no mechanical displacement of the metasurface structure. This photoconductive mechanism provides continuous, reversible control of the substrate properties and potentially enables rewritable spatial modulation patterns. However, the achievable electromagnetic modulation is accompanied by additional dissipative losses associated with the photoinduced conductivity.

In this paper, we revisit and extend the experimental results previously reported in [29] by considering a metasurface antenna realized through the conventional approach of printing subwavelength metallic elements on a high-resistivity silicon substrate. In this configuration, optical illumination modifies the substrate permittivity, which in turn alters the effective surface reactance experienced by the surface wave. This results in a controlled variation of the surface-wave propagation and of its conversion into leaky-wave radiation, enabling optical modulation of the antenna gain. The experimental results demonstrate that significant gain variations can be achieved under moderate optical power densities, confirming the effectiveness of photoconductive control in metasurface antennas.

Building on these findings, we then introduce a new concept that departs from the traditional paradigm of printed metasurfaces. Specifically, we propose an antenna architecture in which the metasurface functionality is achieved without any metallic patterning, relying instead on the direct optical modulation of a silicon substrate. In this approach, the spatial distribution of the substrate's complex permittivity—controlled by optical illumination—effectively synthesizes the required surface reactance profile. As a result, surface-wave excitation and radiation can be engineered purely through photonic means, without the need for patterned conductive elements. The concept is illustrated in Fig. 1.

This concept opens the way to a new class of fully photonic, reconfigurable antennas, in which electromagnetic behavior is dynamically controlled by light. Such an approach offers significant advantages in terms of speed, flexibility, and system integration, while eliminating the constraints associated with fixed metallic patterns and electronic tuning networks.

The remainder of the paper is organized as follows. Section 2 describes the photoconductive principle and the extraction of the complex permittivity under optical illumination. Section 3 presents the design and fabrication of the metasurface antenna based on printed elements on silicon, together with the corresponding experimental validation. Section 4 introduces the concept of fully silicon-based antennas and its numerical demonstration. Finally, conclusions are drawn in Section 5.

2. Photoconductive effect

The photoconductive effect is a fundamental phenomenon in semiconductors whereby optical illumination generates free charge carriers and increases the electrical conductivity of the material.

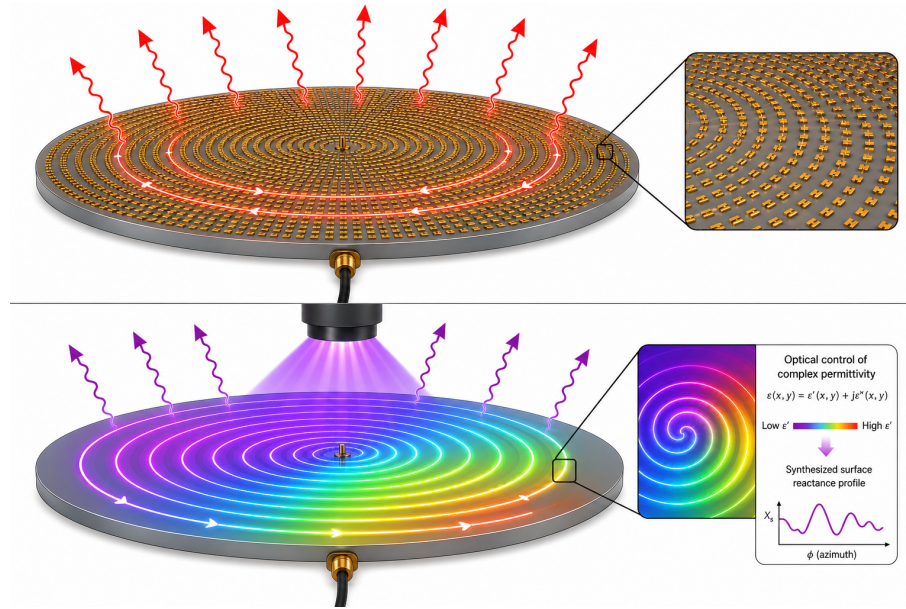


Fig. 1. Comparison between a conventional printed metasurface antenna (top) and the proposed fully photonic metasurface antenna (bottom). In the conventional approach, a dense array of metallic printed elements synthesizes the surface reactance profile required to transform the cylindrical surface wave launched by a centrally fed monopole into radiated waves. In the proposed architecture, the same functionality is achieved without metallic patterning: a spatially varying complex permittivity profile is directly induced inside the silicon substrate through structured optical illumination, here illustrated with a spiral optical pattern. The optically controlled permittivity distribution synthesizes the desired surface reactance and enables dynamic manipulation of surface-wave propagation and radiation entirely through photonic means. The RF excitation is provided through a backside coaxial feed connected to the central monopole in both configurations.

When the incident photon energy exceeds the semiconductor band-gap energy E_g , electron–hole pairs are generated, resulting in a local conductivity variation $\Delta\sigma$. The interaction between optical radiation and silicon depends on several material and optical parameters, including the optical power density, illumination wavelength, carrier mobility, carrier lifetime, and optical absorption coefficient α [30–39]. The resulting photoconductivity distribution is governed by the combined effects of optical absorption and carrier diffusion, as discussed in [38]. The ambipolar diffusion length, which characterizes the transport of photogenerated carriers within the silicon substrate, is defined as

$$L = \sqrt{\frac{2k_B T \tau_r}{q} \frac{\mu_n \mu_p}{\mu_n + \mu_p}} \quad (1)$$

where k_B is the Boltzmann constant, q is the elementary charge, T is the absolute temperature, μ_n and μ_p are the electron and hole mobilities, respectively, and τ_r is the carrier recombination lifetime. Following the formulation proposed by Platte and Sauerer [38], the effects of optical absorption, carrier diffusion, and surface recombination can be incorporated through the optical absorption coefficient α , the ambipolar diffusion length L , the surface recombination velocity v_s , and the carrier lifetime τ_r . The resulting maximum photoconductivity $\Delta\sigma_m$ and effective plasma

depth d_e are given by

$$\Delta\sigma_m = \frac{\Delta\sigma_0}{1 + \alpha L} \left(\frac{1}{\alpha L} \frac{\alpha L^2 + v_s \tau_r}{L + v_s \tau_r} \right)^{\frac{-\alpha L}{1 - \alpha L}} \quad (2)$$

$$d_e = \frac{1}{\alpha} \left(\frac{L(1 + \alpha L) + v_s \tau_r}{L + v_s \tau_r} \right) \left(\frac{1}{\alpha L} \frac{\alpha L^2 + v_s \tau_r}{L + v_s \tau_r} \right)^{\frac{\alpha L}{1 - \alpha L}} \quad (3)$$

Table 2 summarizes the material, optical, photoconductive, and electromagnetic parameters involved in the proposed model. In addition to the intrinsic properties of high-resistivity silicon, the table reports the quantities governing carrier generation, diffusion, and recombination processes, together with the derived parameters used to describe the photo-induced conductivity and the corresponding microwave dielectric response.

Under optical illumination with photon energy exceeding the silicon bandgap energy, electron-hole pairs are generated within the illuminated region. Assuming low-level injection conditions, the excess electron and hole concentrations are approximately equal ($\Delta n \approx \Delta p$), leading to a conductivity increase

$$\Delta\sigma_0 = q(\mu_n + \mu_p)\Delta n, \quad (4)$$

The conductivity $\Delta\sigma_0$ represents the conductivity variation associated with carrier generation prior to diffusion and recombination effects. It serves as the input parameter of the diffusion model described by Eqs. (2) and (3), yielding the effective photoconductivity distribution inside the silicon substrate.

The quantity Δn represents the excess carrier concentration generated by optical illumination with respect to the intrinsic carrier concentration n_i . Under low-level injection conditions, the excess electron and hole concentrations generated are approximately equal, i.e., $\Delta n \approx \Delta p$. For high-resistivity silicon under optical illumination, the excess carrier concentration is typically much larger than the intrinsic one, i.e., $\Delta n \gg n_i$. Therefore, the photoinduced conductivity is primarily determined by the generated carriers. The excess carrier concentration generated by optical illumination can be related to the incident optical power density as

$$\Delta n = \frac{P_{\text{opt}}(1 - R)\tau_r \lambda}{h c d_p} (1 - e^{-\alpha d_p}), \quad (5)$$

where P_{opt} is the optical power density, R is the optical reflectivity, τ_r is the carrier recombination lifetime, λ is the optical wavelength, α is the absorption coefficient, and d_p is the optical penetration depth. We note that the absorption coefficient α appearing in both the carrier-generation model in Eq. (5) and in the effective plasma-depth expression in Eq. (3) is a function of the optical wavelength: $\alpha = \alpha(\lambda_{\text{opt}})$. In the former case, it determines the absorbed optical power and the penetration depth d_p , whereas in the latter it enters the diffusion-based model used to evaluate the effective plasma depth d_e . This expression shows that Δn increases with optical power density, carrier lifetime, and wavelength, while it is also governed by the fraction of optical power absorbed within silicon through the term $(1 - e^{-\alpha d_p})$. Since the optical penetration depth is inversely proportional to the absorption coefficient ($d_p \approx 1/\alpha$), shorter wavelengths, characterized by larger values of α , generate carriers in a thinner region close to the illuminated surface. Conversely, longer wavelengths penetrate deeper into the silicon substrate, producing a more distributed carrier generation profile and a larger effective photoconductive volume. It is worth noting that while the optical penetration depth d_p identifies the region where photons are absorbed and carriers are initially generated, the effective plasma depth d_e accounts for the subsequent carrier diffusion and recombination processes. As a result, d_e generally exceeds d_p , particularly in high-resistivity silicon where the diffusion length can be significantly larger than

the optical absorption depth. Figure 3 illustrates the dependence of the optical penetration depth d_p on the illumination wavelength for the high-resistivity silicon substrate considered in this work. While d_p is solely determined by the wavelength-dependent optical absorption coefficient, d_e additionally accounts for carrier diffusion and surface recombination effects [40]. The comparison highlights the increasing depth of the photoconductive region at longer wavelengths and the significant role that carrier transport plays in extending the effective plasma volume beyond the optical absorption region. It should be noted that, for a finite-thickness silicon wafer, the excess carrier density would be more rigorously obtained by solving the ambipolar diffusion equation with appropriate boundary conditions at both the illuminated surface and the backside metallized interface. In the present configuration, the optical penetration depth at 971 nm ($d_p \approx 100 \mu\text{m}$) is smaller than the substrate thickness ($h=300 \mu\text{m}$), so that photocarrier generation is mainly concentrated in the upper portion of the substrate. The adopted model is therefore expected to capture the main physical mechanism of optical tuning, although finite-thickness and backside recombination effects may quantitatively modify the effective photoconductivity. A more rigorous treatment including these effects could be considered in future work.

2.1. Drude model at microwave frequencies

The generated free carriers modify the electromagnetic properties of silicon through the increase of its electrical conductivity. At microwave frequencies, the carrier dynamics can be described using the classical Drude model. The frequency-dependent complex conductivity of the illuminated silicon substrate is expressed as

$$\sigma(\omega) = \frac{\sigma_{\text{dark}} + \Delta\sigma_m}{1 + j\omega\tau_m}, \quad (6)$$

where σ_{dark} is the dark conductivity of the silicon substrate (see Fig. 2), $\Delta\sigma_m$ is the effective photoconductivity obtained from Eq. (2), and τ_m denotes the carrier momentum relaxation time. Separating the real and imaginary components yields

$$\sigma'(\omega) = \frac{\sigma_{\text{dark}} + \Delta\sigma_m}{1 + \omega^2\tau_m^2}, \quad \sigma''(\omega) = \frac{\omega\tau_m(\sigma_{\text{dark}} + \Delta\sigma_m)}{1 + \omega^2\tau_m^2}. \quad (7)$$

The corresponding complex permittivity can then be written as

$$\varepsilon(\omega) = \varepsilon_s + \frac{\sigma''(\omega)}{\omega\varepsilon_0} - j\frac{\sigma'(\omega)}{\omega\varepsilon_0}, \quad (8)$$

where ε_s is the relative permittivity of unilluminated silicon and ε_0 is the vacuum permittivity. The real and imaginary parts of the conductivity in Eq. (8) play different physical roles. The real part of the conductivity σ' contributes to the imaginary part of the permittivity and is therefore responsible for the increase of microwave losses. Conversely, the imaginary part of the conductivity, σ'' , contributes to the real part of the permittivity and introduces a dispersive variation of the dielectric constant.

It is important to distinguish between the carrier recombination lifetime τ_r and the momentum relaxation time τ_m . The former governs the average survival time of photogenerated carriers and therefore determines the excess carrier concentration Δn produced under optical illumination. The latter characterizes the average time between carrier scattering events and controls the microwave response through the Drude model. Unlike τ_r , which is mainly determined by bulk and surface recombination mechanisms, τ_m is directly related to the carrier mobility through the relation $\tau_m = \mu m^*/q$ and can therefore depend on the photogenerated carrier concentration. As the excess carrier density Δn increases, carrier-carrier interactions, impurity screening, and mobility degradation may modify the momentum relaxation time, making τ_m weakly dependent on the illumination level. In silicon, τ_r is typically in the μs range, whereas τ_m is several orders

Category	Parameter (Symbol)	Typical Value (High-Resistivity Si, 300 K)	Unit	Description / Role in the Model
1. INTRINSIC SILICON PROPERTIES				
Relative permittivity	ϵ_r	11.68	–	Static relative permittivity of silicon
Bandgap energy	E_g	1.12	eV	Silicon bandgap energy
Electron mobility	μ_n	1350	$\text{cm}^2/(\text{V}\cdot\text{s})$	Electron mobility
Hole mobility	μ_p	480	$\text{cm}^2/(\text{V}\cdot\text{s})$	Hole mobility
Electron effective mass	m_n^*	$0.26 m_0$	kg	Effective mass of electrons
Hole effective mass	m_p^*	$0.39 m_0$	kg	Effective mass of holes
Intrinsic carrier concentration	n_i	1.0×10^{10}	cm^{-3}	Equilibrium carrier concentration at 300 K
Resistivity (high-resistivity Si)	ρ	$> 10^4$	$\Omega \cdot \text{cm}$	Dark-state resistivity of the silicon wafer
Dark conductivity	$\sigma_{\text{dark}} = 1/\rho$	$10^{-4} - 10^{-2}$	S/m	Electrical conductivity before illumination (baseline losses)
2. CARRIER GENERATION AND TRANSPORT PARAMETERS				
Carrier recombination lifetime	τ_r	10 – 1000	μs	Average lifetime of photo-generated carriers
Momentum relaxation time	τ_m	$\sim 1.0 \times 10^{-13}$	s	Carrier momentum relaxation time (Drude model)
Surface recombination velocity	v_s	$10^2 - 10^4$	cm/s	Velocity of carrier recombination at surface
Ambipolar diffusion length	$L = \sqrt{\frac{2k_B T \tau_r}{q} \frac{\mu_n \mu_p}{\mu_n + \mu_p}}$	50 – 500	μm	Characteristic length for ambipolar diffusion
Constants used: $k_B = 1.38 \times 10^{-23}$ J/K (Boltzmann constant), $q = 1.60 \times 10^{-19}$ C (elementary charge), $T = 300$ K				
3. OPTICAL PARAMETERS (AT NORMAL INCIDENCE)				
Carrier reach wavelength	λ	806 nm / 971 nm	nm	Laser wavelength used for optical excitation
Optical reflectivity	R	0.30 – 0.40	–	Surface reflectivity of silicon
Absorption coefficient @ 806 nm	α_{806}	$\sim 1.0 \times 10^4$	cm^{-1}	Optical absorption coefficient at 806 nm
Absorption coefficient @ 971 nm	α_{971}	$\sim 1.0 \times 10^2$	cm^{-1}	Optical absorption coefficient at 971 nm
Optical penetration depth @ 806 nm	$d_p = 1/\alpha_{806}$	~ 1	μm	Depth where light is absorbed (1/e intensity)
Optical penetration depth @ 971 nm	$d_p = 1/\alpha_{971}$	~ 100	μm	Depth where light is absorbed (1/e intensity)
Incident optical power density	P_{opt}	(variable)	W/cm^2	Optical power per unit area (input variable)
4. DERIVED PHOTOCONDUCTIVE QUANTITIES				
Excess carrier concentration	$\Delta n (\approx \Delta p)$	$\frac{P_{\text{opt}}(1-R)\tau_r\lambda}{hcd_p}(1-e^{-\alpha d_p})$	cm^{-3}	Excess electron (and hole) density generated by optical illumination
Photoconductivity from generation (before diffusion and recombination)	$\Delta\sigma_0$	$q(\mu_n + \mu_p)\Delta n$	S/m	Conductivity increase predicted directly from the generated carriers (not yet corrected for transport losses). $\Delta\sigma_0$ is different from σ_{dark} .
Maximum effective photoconductivity (after considering transport effects)	$\Delta\sigma_m$	see eq. (2)	S/m	Maximum photoconductivity at the surface ($z = 0$) after accounting for absorption, diffusion and surface recombination.
Effective plasma depth	d_e	see eq. (3)	μm	Equivalent thickness of the conductive layer including diffusion and recombination effects.
Total (DC) conductivity used in EM model	$\sigma_{\text{tot}} = \sigma_{\text{dark}} + \Delta\sigma_m$	–	S/m	Total conductivity of illuminated silicon used in the Drude model.
σ_{dark} : conductivity before illumination (baseline losses). $\Delta\sigma_0$: photoconductivity from generation (no transport effects). $\Delta\sigma_m$: effective (maximum) photoconductivity after including absorption, diffusion and surface recombination. σ_{tot} : total conductivity entering the microwave electromagnetic model.				
5. ELECTROMAGNETIC MODEL (DRUDE MODEL)				
Complex conductivity	$\sigma(\omega)$	$\frac{\sigma_{\text{tot}}}{1 + j\omega\tau_m}$	S/m	Drude complex conductivity at angular frequency ω
Complex permittivity	$\epsilon(\omega)$	$\epsilon_s + \frac{\sigma''(\omega)}{\epsilon_0\omega} - j \frac{\sigma'(\omega)}{\epsilon_0\omega}$	–	Photoinduced complex permittivity. $\sigma'(\omega)$: real part (dissipative), $\sigma''(\omega)$: imaginary part (reactive).
FUNDAMENTAL CONSTANTS AND REFERENCE VALUES (300 K) - Planck constant: $h = 6.626 \times 10^{-34}$ J·s - Boltzmann constant: $k_B = 1.38 \times 10^{-23}$ J/K - Elementary charge: $q = 1.60 \times 10^{-19}$ C - Speed of light: $c = 3.00 \times 10^8$ m/s - Vacuum permittivity: $\epsilon_0 = 8.854 \times 10^{-12}$ F/m - Electron rest mass: $m_0 = 9.11 \times 10^{-31}$ kg				

Fig. 2. Material, optical, photoconductive, and electromagnetic parameters used in the silicon photoconductivity model.

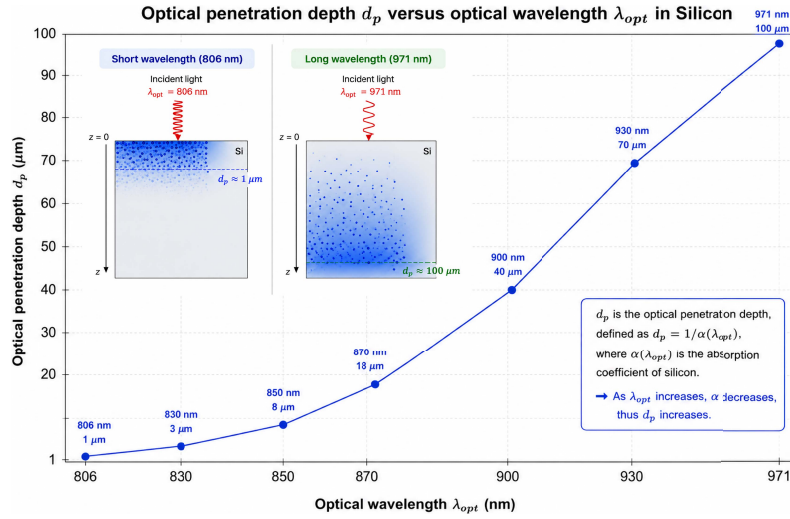


Fig. 3. Optical penetration depth d_p versus optical wavelength for the high-resistivity silicon substrate.

of magnitude smaller and generally falls in the sub-picosecond to picosecond range. For standard silicon substrates, values of τ_m are commonly reported between a few tenths of a picosecond and approximately 1 ps. In contrast, high-resistivity and high-purity silicon substrates exhibit reduced impurity scattering and higher carrier mobility, allowing τ_m to approach or even exceed 1 ps under favorable conditions. Consequently, a certain degree of uncertainty remains in the choice of τ_m . A value of $\tau_m = 5$ ps yields $\omega\tau_m = \sigma''/\sigma' \approx 1$ at 30 GHz (in the following plots in this section, we will assume the more realistic value $\tau_m = 1$ ps). The microwave complex permittivity of high-resistivity single-crystal silicon under optical illumination can be experimentally extracted using bistatic free-space measurements in the Ka-band. Measurements performed under continuous-wave illumination at wavelengths of 806 nm and 971 nm are reported in [41] and provide experimentally validated material parameters for the design of photoconductive metasurfaces.

Figure 4 illustrates the frequency dependence of the photoinduced complex conductivity and relative permittivity of the high-resistivity silicon substrate under optical illumination. The results are obtained from the carrier-generation model combined with the Drude formulation, assuming a momentum relaxation time of $\tau_m = 1$ ps; the other parameters are reported in the caption. As expected, increasing the optical power density increases the generated carrier concentration and, consequently, the magnitude of both the conductivity and dielectric perturbation.

3. Metasurface antenna with printed elements on a silicon substrate

Here, we outline the fabrication process of a silicon-based Ka-band MTS antenna, which operates on the principle of surface wave excitation. The chosen material allows for the control of the microwave complex photoconductivity of the silicon substrate by laser beam illumination, leading to the consequent modulation of the antenna's gain. The metasurface (MTS) antenna is fabricated on a 4-inch, 300 μm -thick high-resistivity silicon (HiRes Si) wafer [29], characterized by a relative permittivity of 11.7. The printed texture consists of subwavelength elliptical metallic patches arranged on a regular lattice with period $p = 1.5\text{mm}$ (approximately $\lambda/6.6$ at 30 GHz). The dimensions and orientation of the ellipses are designed to synthesize the required anisotropic surface reactance. The fabrication process follows standard photolithographic techniques. A metallic layer is first deposited on the silicon substrate and patterned using photoresist coating

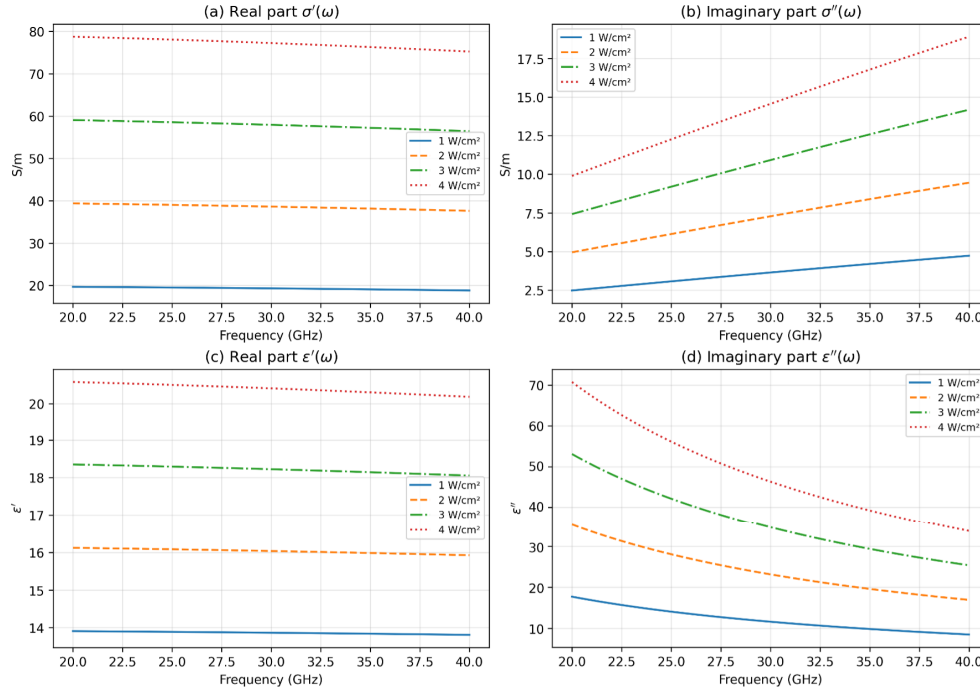


Fig. 4. Frequency dependence of the complex conductivity and permittivity of optically illuminated high-resistivity silicon in the 30–40 GHz range for optical power densities $P_{\text{opt}} = 0.24, 0.34, \text{ and } 0.47 \text{ W/cm}^2$. The calculations are performed using the same material and photoconductive parameters adopted in the experimental demonstration reported in [41], namely $\epsilon_s = 11.68$, $\sigma_{\text{dark}} = 10^{-5} \text{ S/m}$, $\tau_m = 1 \text{ ps}$, $\tau_r = 5.8 \text{ } \mu\text{s}$, $L = 116 \text{ } \mu\text{m}$, $v_s = 400 \text{ cm/s}$, $\lambda_{\text{opt}} = 971 \text{ nm}$, $\alpha_{971} = 100 \text{ cm}^{-1}$, $d_p = 100 \text{ } \mu\text{m}$, $\mu_n = 1350 \text{ cm}^2/(\text{V} \cdot \text{s})$, and $\mu_p = 480 \text{ cm}^2/(\text{V} \cdot \text{s})$. Panels (a) and (b) show the real and imaginary parts of the conductivity, $\sigma'(\omega)$ and $\sigma''(\omega)$, respectively, whereas panels (c) and (d) report the corresponding real and imaginary parts of the permittivity, $\epsilon'(\omega)$ and $\epsilon''(\omega)$. The photoconductivity is assumed to follow the experimentally determined relationship $\Delta\sigma_m \approx 20P_{\text{opt}} \text{ (S/m)}$, where P_{opt} is expressed in W/cm^2 .

and mask-based etching to define the elliptical elements. A second metallic layer is subsequently formed on the backside to realize the ground plane. Finally, the silicon substrate is etched to create a central hole, enabling the insertion of the inner conductor of a coaxial probe. This conductor acts as a monopole feed, exciting a surface wave on the metasurface. Figure 5 shows a photograph of the fabricated metasurface antenna, with a detail of the central monopole feed in Fig. 5(a) and the corresponding numerical model used for full-wave simulations Fig. 5(b). In the numerical model, the metallic regions are shown in orange, while the substrate is divided into non-illuminated (green, $\epsilon_r = 11.51$) and illuminated (purple, complex permittivity) areas. The experimental characterization is performed in an anechoic environment, as illustrated in Fig. 5(c). The metasurface antenna is mounted on an optical bench and illuminated by a fiber-coupled laser source, whose beam is directed onto the silicon substrate to induce photoconductivity. A circularly polarized horn antenna is used as a receiver, while the antenna under test is placed on a rotating stage to measure the azimuth radiation pattern under both dark and illuminated conditions. The measured radiation patterns are reported in Fig. 5(d) for increasing optical power densities at a wavelength of 971 nm. In the absence of illumination (OFF state), the antenna exhibits broadside radiation with a maximum gain of approximately 20 dB. As the optical power

density increases, a progressive reduction of the main lobe is observed, reaching a decrease of about 6.7 dB at the highest illumination level. This phenomenon is likewise ascribed to variations in the penetration depth of HR silicon material with optical wavelength, which in turn influences the imaginary part of its permittivity. At the same time, slight modifications of the pattern shape and secondary lobes are visible, indicating that optical excitation affects both the real and imaginary parts of the substrate permittivity. These results confirm that the photoconductive effect in silicon enables effective optical control of the antenna radiation characteristics.

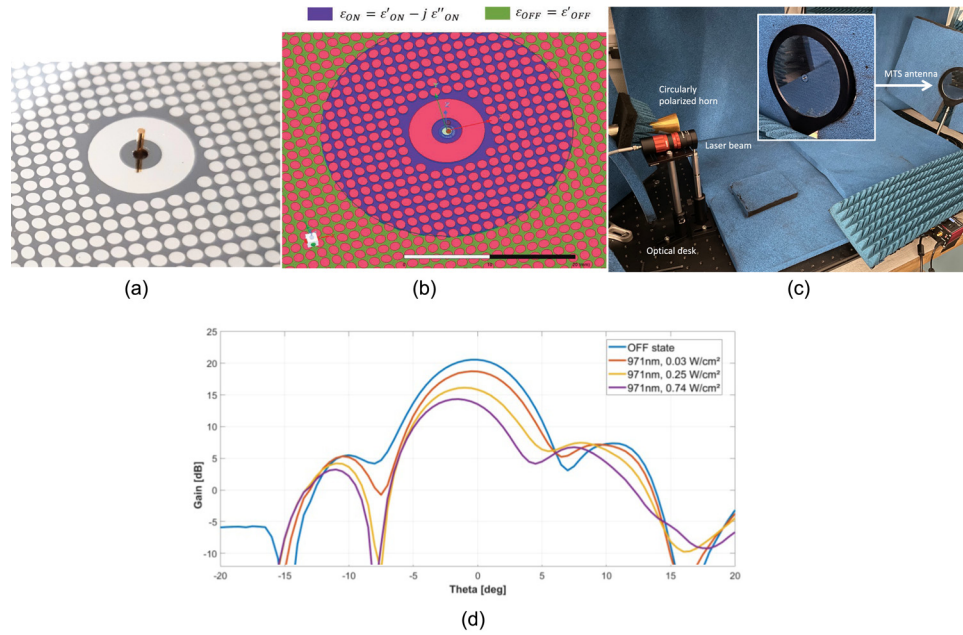


Fig. 5. (a) image of the central part of the Silicon antenna with the monopole feed. (b) Top view of the numerical model showing the metallic pattern and the substrate regions: non-illuminated (green, $\epsilon_r = 11.51$) and illuminated (purple, complex permittivity from measurements). (c) experimental set-up. (d) Measured RHCP pattern for the Si-based MTS antenna at 29.5 GHz under 971 nm wavelength optical control at various power densities, as indicated in the inset.

Under optical illumination, the light penetrates into the silicon substrate and modifies its complex permittivity. This change affects both the real and imaginary components, which in turn influence the antenna efficiency and gain. The variation of the real part of the permittivity alters the propagation constant of the surface wave launched by the feed, leading to a mismatch with the metasurface impedance modulation. This affects the conversion mechanism from surface to leaky waves and results in modifications of the radiation pattern. At the same time, the increase of the imaginary part of the permittivity introduces additional Ohmic losses, reducing the amount of power effectively radiated. All in all, the measured gain reduction under optical illumination can be associated with the combined effect of different mechanisms. In particular, the photoinduced variation of the silicon electromagnetic properties may alter the surface-wave propagation and consequently the SW-to-LW conversion process, while the increased photoconductivity also introduces additional dissipative losses. A variation in the feed coupling efficiency may also contribute to the observed gain reduction, although the measured input matching suggests that this effect is likely less significant than the changes associated with the SW-to-LW conversion process and the additional dissipative losses. The available experimental results, however, do not

allow these contributions to be quantitatively separated. Non-uniform illumination also affects the effective aperture efficiency.

4. Fully silicon-based antenna concept

The photoinduced modification of the complex permittivity changes the equivalent surface impedance experienced by electromagnetic waves at the silicon interface. In metasurface antennas based on surface-wave excitation, this effect alters both the propagation constant and the leakage characteristics of the guided mode. Consequently, optical illumination provides a powerful mechanism for dynamically controlling antenna characteristics. In this section, we analyze this novel configuration in which the metasurface functionality is achieved without any metallic patterning, relying exclusively on the optical modulation of a silicon substrate.

4.1. TM dispersion equation in absence of illumination

In the absence of optical illumination, the structure can be described as a grounded dielectric slab of thickness d . The corresponding surface-wave dispersion relation is obtained by imposing the transverse resonance condition between the input admittance of the short-circuited slab and the modal impedance in the air region. This gives $Y_{\text{air}}^{\text{TM}} + Y_{\text{slab}}^{\text{TM}} = 0$ where $Y_{\text{air}}^{\text{TM}}$ represents the TM modal admittance associated with the evanescent field in the air region above the substrate, $Y_{\text{slab}}^{\text{TM}}$ is the input admittance of the grounded dielectric slab supporting the confined surface wave. These two admittances are effectively connected in parallel at the air–dielectric interface, and the resonance condition is obtained when their sum vanishes. By introducing the explicit expressions of the two terms, one has the well-known expression

$$-\frac{1}{\alpha_0} + \frac{\varepsilon_s}{k_1} \cot(k_1 d) = 0 \quad (9)$$

where $k_{z1} = \sqrt{k_0^2 \varepsilon_s - k_p^2}$, $\alpha_0 = \sqrt{k_p^2 - k_0^2}$, $k_0 = \frac{\omega}{c}$, $k_1 = k_0 \sqrt{\varepsilon_s}$ and ε_s is the unperturbed relative permittivity of the silicon. The surface-wave propagation constant is therefore $k_p = k_{\text{sw}}$, where k_{sw} is the real solution of the above dispersion equation satisfying $k_p > k_0$. For a grounded silicon slab with $d = 600 \mu\text{m}$, the transverse resonance condition predicts a transition around $f_0 \approx 38 \text{ GHz}$, approximately corresponding to $k_{z1} d = \pi/2$. At this frequency the effective slab reactance changes sign, marking the onset of a TE-type surface-wave solution. However, the TM branch does not necessarily terminate at this point since a real solution can be found. Since a vertical electric dipole primarily couples to TM-polarized fields, this continued TM branch remains the relevant mode for dipole excitation. In the present work, however, the holographic antenna is operated at a slightly lower frequency (30 GHz) to avoid possible excitation of the TE mode due to feed imperfections.

4.2. TM dispersion equation in presence of optical illumination

Under optical illumination, the carrier generation process modifies the electromagnetic properties of a thin region located at the top of the silicon substrate. The illuminated region, whose thickness is equal to the optical penetration depth (d_p), is characterized by a complex permittivity $\varepsilon(\omega)$ defined by the Drude model in Eq. (8), while the remaining portion of the substrate retains the unperturbed permittivity (ε_s). The structure can therefore be modeled as a grounded two-layer dielectric slab, consisting of a photo-activated layer of thickness (d_p) over an unperturbed silicon region of thickness ($d - d_p$). We note that the photogenerated carrier concentration is not strictly uniform within the illuminated region but follows approximately an exponential decay governed by the optical absorption coefficient. A more rigorous treatment would model the graded profile using a multilayer or continuously varying medium with depth-dependent permittivities. While this would improve accuracy and is a valuable direction for future work, the equivalent

uniform-layer model provides a reasonable first-order approximation that captures the key physics of the optically controlled reconfiguration mechanism while keeping the analysis tractable.

The TM surface-wave dispersion relation is obtained by imposing the transverse resonance condition at the air–substrate interface. Using the transmission-line representation of the stratified medium, the modal admittance seen from the interface is obtained by cascading the transmission lines associated with the illuminated and unilluminated regions. The resulting exact dispersion equation is

$$-\frac{1}{\sqrt{k_p^2 - k_0^2}} + \frac{\varepsilon(\omega)}{k_{z2}} \frac{\frac{\varepsilon_s}{k_{z1}} \cot[k_{z1}(d - d_p)] \frac{\varepsilon(\omega)}{k_{z2}} \tan(k_{z2}d_p)}{\frac{\varepsilon(\omega)}{k_{z2}} + \frac{\varepsilon_s}{k_{z1}} \cot[k_{z1}(d - d_p)] \tan(k_{z2}d_p)} = 0, \quad (10)$$

where $k_{z1} = \sqrt{\varepsilon_s k_0^2 - k_p^2}$ and $k_{z2} = \sqrt{\varepsilon(\omega) k_0^2 - k_p^2}$. Equation (10) represents the exact transmission-line formulation of the illuminated structure and fully accounts for the phase accumulation and impedance transformation occurring within the photogenerated region. Optical illumination modifies the dispersion characteristics through the complex permittivity $\varepsilon(\omega)$, whose value is determined by the carrier concentration generated within the penetration-depth layer. The solution of the dispersion equation in Eq. (10) is generally a complex quantity, $k_p = \beta_p - j\alpha_p$, where the real part β_p represents the phase propagation constant of the surface wave, while the imaginary part α_p accounts for the attenuation of the mode along the propagation direction. The presence of optical losses and the finite conductivity of the photogenerated plasma layer therefore lead to a complex modal propagation constant whose value depends on both frequency and optical illumination conditions.

To further quantify the impact of optical illumination on the propagation characteristics of the supported TM surface-wave mode, the exact dispersion equation in Eq. (10) was numerically solved for different optical power densities. The analysis was performed using the same photoconductive silicon parameters adopted in the experimental demonstration of [41], assuming an illumination wavelength of 971 nm and a substrate thickness of 600 μm . In addition to the exact dispersive model, a constant-permittivity approximation was considered, in which the complex permittivity of the photoexcited region was assumed frequency-independent and fixed to the value predicted by the Drude model at the central frequency of 30 GHz. Figure 6 compares the resulting normalized propagation constants in the frequency range from 28 to 32 GHz. Specifically, panel (a) reports the normalized phase constant $\text{Re}(k_p d)$, while panel (b) shows the normalized attenuation constant $-\text{Im}(k_p d)$ for different optical power levels. Solid curves correspond to the exact frequency-dependent Drude model, whereas dashed curves represent the constant-permittivity approximation evaluated at 30 GHz. The comparison provides a direct assessment of the influence of the frequency dispersion of the photoexcited silicon on both phase propagation and modal attenuation, while highlighting the modifications induced by the photogenerated carriers within the illuminated region.

4.3. Depicting holographic modulation on silicon

The fully silicon-based antenna configuration is investigated through full-wave simulations. The considered layout is shown in the inset of Fig. 7, where the metasurface functionality is synthesized by an optically induced modulation of the substrate arranged in an Archimedean spiral-like distribution (shown in the inset). The fully silicon-based antenna concept analyzed in this Section has been designed on a 600 μm -thick HR silicon substrate, selected to support the desired TM surface-wave dispersion at 30 GHz. The spatial variation of the photoconductive region enables the control of the equivalent surface reactance without relying on any metallic patterning. The structure is excited by a simple monopole feed inserted through the substrate, without any surrounding metallic patch or matching structure. The spiral periodicity is specifically designed to match the wavelength of the TM surface wave supported by the photoconductively

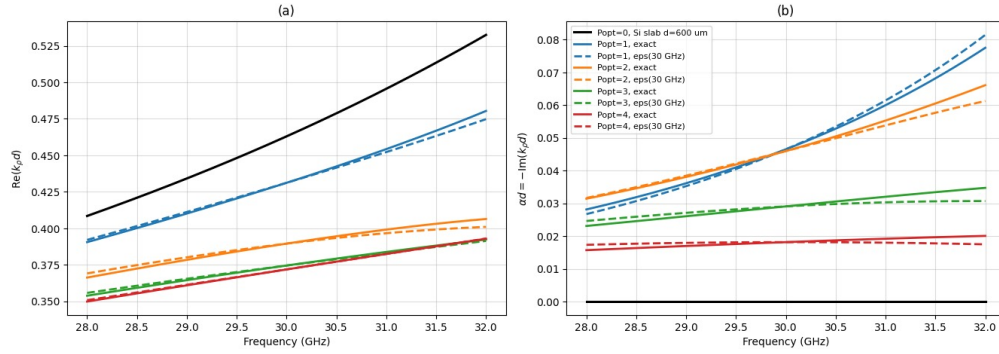


Fig. 6. Normalized complex propagation constant obtained from the exact TM dispersion equation for a grounded high-resistivity silicon substrate of thickness $d = 600 \mu\text{m}$, illuminated at $\lambda_{\text{opt}} = 971 \text{ nm}$. Panel (a) shows the normalized phase constant $\text{Re}(k_{\rho}d)$, whereas panel (b) reports the normalized attenuation constant $-\text{Im}(k_{\rho}d)$, in the frequency range 28–32 GHz. Solid lines correspond to the exact dispersive model of the photoexcited silicon, while dashed lines are obtained by assuming a frequency-independent complex permittivity equal to its value at 30 GHz, i.e., $\varepsilon(\omega) = \varepsilon(2\pi \times 30 \text{ GHz})$. The calculations were performed using the same material and photoconductive parameters adopted in the experimental demonstration reported in [41], with $\tau_m = 1 \text{ ps}$ and an experimentally determined photoconductivity variation given by $\Delta\sigma_m \approx 20P_{\text{opt}}$ (S/m), where P_{opt} is expressed in W/cm^2 . Results are reported for optical power densities of 1, 2, 3, and 4 W/cm^2 . The black curve corresponds to the reference case $P_{\text{opt}} = 0$, representing the conventional TM surface-wave mode supported by an unilluminated grounded silicon slab of thickness $d = 600 \mu\text{m}$.

activated grounded silicon substrate under the average optical illumination condition. The corresponding surface-wave wavelength is obtained from the solution of the dispersion equation of the activated substrate. Once the spiral periodicity is defined at the selected operating condition, its geometrical distribution remains fixed. Variations of the optical illumination may modify the surface-wave propagation constant and consequently introduce a departure from the nominal phase-matching condition. Spatial non-uniformities of the illumination may similarly produce local variations of the surface-wave propagation characteristics. In the present design, however, the characteristic dimensions of the spiral modulation remain sufficiently large compared with the expected diffusion spreading distance, so that diffusion-induced smoothing is not expected to significantly affect the underlying radiation mechanism.

Under these conditions, the spiral modulation provides the appropriate phase-matching mechanism for the excitation of the (-1) Floquet harmonic at broadside, enabling the conversion of the guided lossy surface wave into a radiated beam normal to the antenna aperture. The corresponding radiation patterns are reported in Fig. 7(b) for different illumination conditions. At 30 GHz, a directive broadside radiation is clearly obtained, confirming that the optically induced reactance profile supports surface-wave excitation and its conversion into leaky-wave radiation. The main lobe exhibits a stable angular position, while its amplitude varies with the optical power density level, demonstrating the ability to control the antenna gain through the photoconductive effect. The overall shape of the pattern remains well defined, with moderate side lobes, indicating that the synthesized reactance distribution effectively mimics the behavior of a conventional metasurface antenna. It should be noted, however, that the overall radiation efficiency remains relatively low. This behavior is expected because the photoconductive activation introduces not only the desired reactive perturbation but also a significant real part of the conductivity. Indeed, according to the Drude model, the reactive permittivity variation and the dissipative conductivity are intrinsically linked. Consequently, increasing the photocarrier concentration enhances the

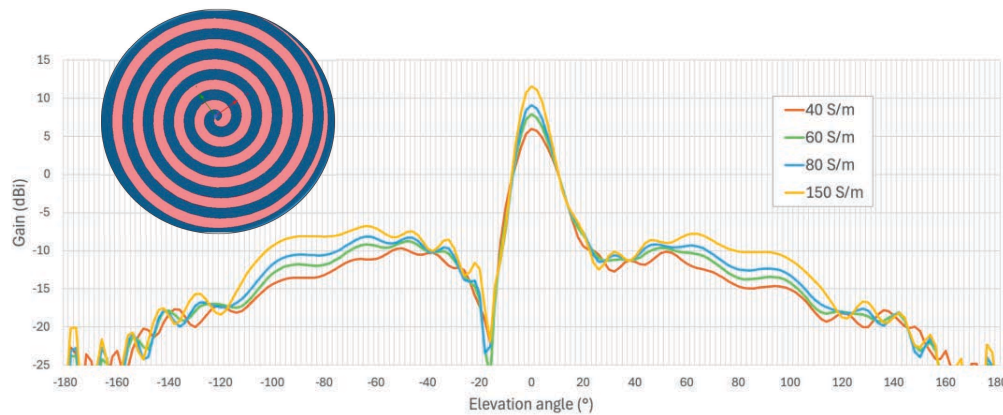


Fig. 7. Fully silicon-based antenna. Simulated radiation patterns at 30 GHz under different illumination levels. In the inset: top view of the spiral-shaped photoconductive modulation used to synthesize the equivalent surface reactance. The structure is designed on a silicon substrate of thickness $d = 600 \mu\text{m}$ and is excited by a central monopole feed with diameter 0.6 mm and length 2.6 mm. The central hole diameter is 1.28 mm, while the optically induced conductive layer has an effective thickness of $100 \mu\text{m}$. The spiral modulation starts from a central region of diameter 10 mm. Photoconductivity values of 40, 60, 80 and 150 S/m correspond to experimental optical power densities of 2.1, 3.1, 4.2 and 7 W/cm^2 respectively at an optical wavelength of 971 nm [41].

tunability of the antenna but also increases Ohmic losses, leading to an inherent trade-off between reconfigurability and radiation efficiency. However, this trade-off can be mitigated through appropriate illumination engineering.

To further highlight the radiation mechanism, the three-dimensional radiation patterns obtained for two different substrate thicknesses are reported in Fig. 8. Figure 8(a,b) correspond to the reference configuration with a substrate thickness of $600 \mu\text{m}$, whereas Fig. 8(c,d) show the response obtained after increasing the substrate thickness to $800 \mu\text{m}$. When the substrate thickness is increased to $800 \mu\text{m}$, the TM transition of the grounded slab is shifted toward lower frequencies, allowing the effective surface impedance at the interface to become globally negative at 30 GHz.

Figure 8 provides a qualitative comparison of the radiation pattern between two substrate thicknesses of $600 \mu\text{m}$ in Fig. 8(a,b) and $800 \mu\text{m}$ Fig. 8(c,d). While the $600 \mu\text{m}$ substrate features the highest broadside gain with a well-formed circular beam and a maximum RHCP gain of approximately 12.95 dB, the $800 \mu\text{m}$ substrate case shows a significant reduction. The sidelobe levels follow the same trend, considerably degrading by employing the thicker substrate. Even if this second example is still able to radiate energy away from the surface (it does not correspond to a non-radiating state), the radiation is substantially weaker (due to the dispersivity of the leakage constant) as the maximum RHCP gain decreases to approximately 4.94 dB and the pointing is no longer at broadside. Indeed, the increase in substrate thickness modifies the surface-wave propagation constant, causing a mismatch between the designed spiral periodicity and the surface-wave wavelength (broadside phase-matching condition is no longer satisfied). Such a difference in behavior between the two substrates is not attributed to variation in input impedance, which has been examined for the two thicknesses: observed variations of the S_{11} coefficient remain limited compared with the magnitude of the gain reduction. In this regard, the dominant mechanism behind the gain decrease is surface-wave dispersion (with respect to the substrate thickness), which corrupts both the phase-matching condition and leaky-wave radiation characteristics. In conclusion, the reduction in gain for the $800 \mu\text{m}$ substrate is mainly attributed to a decrease in surface-wave-to-radiation conversion.

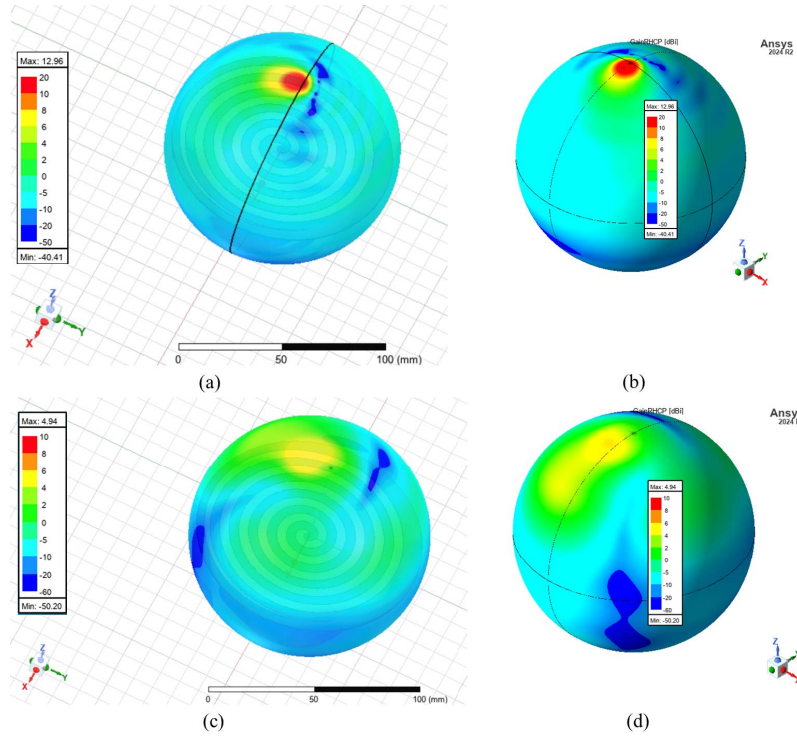


Fig. 8. Three-dimensional radiation patterns of the optically controlled spiral antenna at 30 GHz. (a) and (b) represent the configuration with substrate thickness $d = 600 \mu\text{m}$, characterized by a positive effective surface reactance and supporting the TM surface-wave regime. In (a) it is visible, in the background, the spiral shape of the antenna, while (b) represents the radiation sphere with colored mapping for the radiated field gain. In this case, the guided surface-wave wavelength is matched to the spiral periodicity, enabling efficient excitation of the (-1) Floquet harmonic at broadside. In (c) and (d) the configuration with substrate thickness $d = 800 \mu\text{m}$ is represented and is characterized, at the frequency relevant to the far field plot, by a negative effective surface reactance. The change in the guided wavelength detunes the phase-matching condition with the spiral modulation, suppressing the (-1) Floquet mode and reducing the broadside radiation.

We would like to stress that the fully silicon-based antenna presented in this section is intended as a proof-of-concept demonstration of the proposed optical reconfiguration mechanism. Its validation is presently based on full-wave electromagnetic simulations combined with the photoconductivity model of optically illuminated silicon. Experimental validation of the proposed architecture is currently under development and requires a dedicated setup providing controlled and calibrated optical illumination together with simultaneous microwave characterization. The corresponding experimental assessment is expected to be addressed in the upcoming work.

5. Conclusions

This work builds upon previously reported results on optically controlled metasurface antennas implemented on high-resistivity silicon substrates [29]. In that earlier study, a metasurface realized with printed metallic elements was experimentally characterized in the Ka-band under near-infrared illumination, demonstrating that optical excitation modifies the substrate permittivity and enables control of the antenna gain.

In the present paper, these results are briefly recalled to provide the physical basis for a new antenna concept, in which the metasurface functionality is achieved without any metallic patterning. In this approach, the antenna behavior is entirely governed by the optically induced modulation of the silicon substrate, which enables the synthesis of an equivalent surface reactance. Full-wave simulations show that a simple monopole feed can efficiently excite the resulting surface mode, leading to directive radiation with controllable gain and acceptable input matching.

These findings demonstrate that optical control of a photosensitive substrate can be used not only to tune conventional metasurface antennas, but also to realize fully silicon-based radiating structures. This approach opens the way to a new class of reconfigurable, fully photonic antennas, eliminating the need for metallic patterns and electronic tuning components. Such capabilities offer promising perspectives for high-speed and secure communication systems, where microwave signals can be directly controlled through optical excitation.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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