

Energy-Efficient and Frequency-Agile RF Photonic Beamformer for Next-Generation Space Communications

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ABSTRACT

Next-generation wireless communication systems rely heavily on phased-array antenna systems fed by energy-efficient, compact, squint-free, broadband, and frequency-agile beamforming circuits. Microwave photonic beamformers have shown great potential to overcome the limitations of traditional electronic counterparts and meet these requirements. However, simultaneously achieving high-resolution, ultra-broadband beam steering and dynamically adjustable transmission frequencies for any baseband signal remains challenging. Here, we numerically demonstrate a novel microwave photonic beamformer that leverages phase-change material (PCM)-aided programmability and a frequency conversion unit to address these requirements. A symmetric, directional coupler-based switch employing low-loss PCM enables the development of a compact optical beamforming chip (OBFN) with an energy consumption of 12.1 μ J on a standard silicon-on-insulator platform. The frequency conversion unit, comprising a carrier-suppressed single-sideband (CS-SSB) modulator and a tunable laser source, enables dynamic adjustment of the transmitted frequency for any received baseband signal, offering greater adaptability to user demands and efficient spectrum usage. Together, the proposed architecture provides squint-free beam steering over a field of view of -59.8° to 58.4° , with an angular resolution of 0.92° , and adjustable transmission frequencies covering the entire Ku-Ka band. The ability to dynamically allocate operating frequencies, together with energy-efficient broadband beam steering, makes the proposed architecture promising for emerging LEO satellite constellations and for establishing secure, high-capacity, adaptive communication links between space and ground.

Keywords: Microwave photonics, phase change material, beamforming, silicon photonics, adaptable frequency

INTRODUCTION

Modern space communication systems heavily rely on satellite telecom payloads responsible for processing, receiving/transmitting signals at flexible frequencies. These systems play a pivotal role in 5/6G wireless communications, Earth observation and navigation, deep space exploration, and other applications. An energy-efficient, lightweight, broadband ($\sim$ GHz), and programmable signal processing unit, compatible with technologies such as phased array antennas (PAA) and reconfigurable frequency converters can broaden the capabilities of currently deployed payloads for various applications^{1,2}. PAA systems enabling squint-free dynamic beam steering over a broad bandwidth with improved signal directionality are key components of LEO-based communication systems. Meanwhile, a frequency up/down conversion unit enables efficient signal translation across different RF frequencies, improving spectrum utilization and adaptability to user demands. Integrating these functionalities into a compact and reconfigurable platform can significantly reduce the size, weight, power consumption, and complexity (SWaP-C) of next-generation satellite payloads. Such a versatile architecture can facilitate the dynamic allocation of communication resources in response to changing link conditions, coverage requirements, and spectrum availability. Furthermore, broadband programmability can support multi-band and multi-standard operation, thereby reducing the need for dedicated hardware for individual frequency bands or communication protocols. These capabilities are particularly important for emerging LEO satellite constellations, where high-capacity, adaptive, and energy-efficient payloads are essential for providing reliable and scalable global connectivity.

Microwave photonic-based beam-forming technologies combined with dynamic frequency conversion have significant potential to address these requirements owing to the inherent broadband capability of photonics, low-loss, energy-efficient high-speed signal processing, compactness and immunity to electromagnetic interference^{3,4}. Moreover, the broadband nature of microwave photonics enables squint-free beam steering over a wide frequency range, which is an important requirement for next-generation wireless communication and a well-known limitation of traditional electronic beamformers. However, despite these advantages, the performance of current microwave photonic beamformers based on switchable delay lines or ring resonator delay line-based architectures is primarily constrained by conventional programmability mechanisms. Techniques such as thermo-optic effect and carrier dispersion effect induce relatively small

refractive index modulations, resulting in larger footprints, whereas their volatile operation requires continuous power supply to hold the programmed states. The thermo-optic effect is the most widely used tuning mechanism in microwave photonic beamformers, although thermal crosstalk can further increase the footprint. In recent years, several advances have been reported in thermo-optically controlled optical switchable delay lines (OSDLs), which represent a particularly suitable and stable architecture for broadband beamforming compared with ring resonators, gratings, and other beamforming approaches³. However, the discrete delay tuning provided by OSDLs generally offers a limited number of beam-steering angles, and, in some cases, the number of available angles decreases as the number of antenna elements increases, thereby limiting their applicability to high-resolution and large-scale beamforming. Recent approaches have addressed this limitation by increasing the number of basic delay units with the antenna count or by introducing compensating units before the OSDL, allowing the maximum number of steerable angles to reach 2^m for an m -bit OSDL independently of the antenna count^{5,6}. Nevertheless, both reported structures are based on a 5-bit OSDLs, providing only 32 steerable angles, with beamforming network footprints of $3.9 \times 11 \text{ mm}^2$ ⁵ and $3 \times 8 \text{ mm}^2$ ⁶. Increasing the delay bit depth can improve the angular resolution, but at the expense of a larger footprint.

In our recent work, we numerically addressed the trade-off between footprint and resolution by exploiting a new generation of low-loss phase-change material (PCM), which offers large refractive index modulation, compactness, and non-volatile programmability⁷⁻⁹. The reversible transition between the amorphous and crystalline states of such materials, induced by electrical or optical pulses, produces localized refractive index modulation, enabling reconfigurability in photonic circuits. Exploiting these properties, we demonstrated a 7-bit OSDL-based microwave photonic beamformer providing 128 beam-pointing angles within a footprint of $2.5 \times 3.1 \text{ mm}^2$, smaller than those of lower-bit-depth state-of-the-art beamformers⁸. Moreover, the large index modulation and non-volatile programmability of PCMs contribute to improving the energy efficiency of the architecture. However, in this and the other aforementioned approaches, the transmitted RF frequency through the PAA is fixed for a given received baseband frequency, hindering dynamic frequency adjustment, which represents another important requirement of next-generation wireless communication systems.

Here we extend our previous approach by combining low-loss PCM-aided programmability with a frequency-conversion unit that enables dynamically adjustable transmission. In addition, a symmetric directional-coupler-based PCM switch is introduced to reduce the switching energy compared with our previously reported asymmetric configuration. The proposed architecture provides high-resolution squint-free beam steering together with frequency-agile operation over a broad frequency range spanning Ku-Ka bands, while reducing the energy consumption of the optical beam-forming network. These combined capabilities make the proposed architecture a promising solution for reconfigurable and energy-efficient future space communication systems.

PROPOSED ARCHITECTURE & WORKING PRINCIPLE

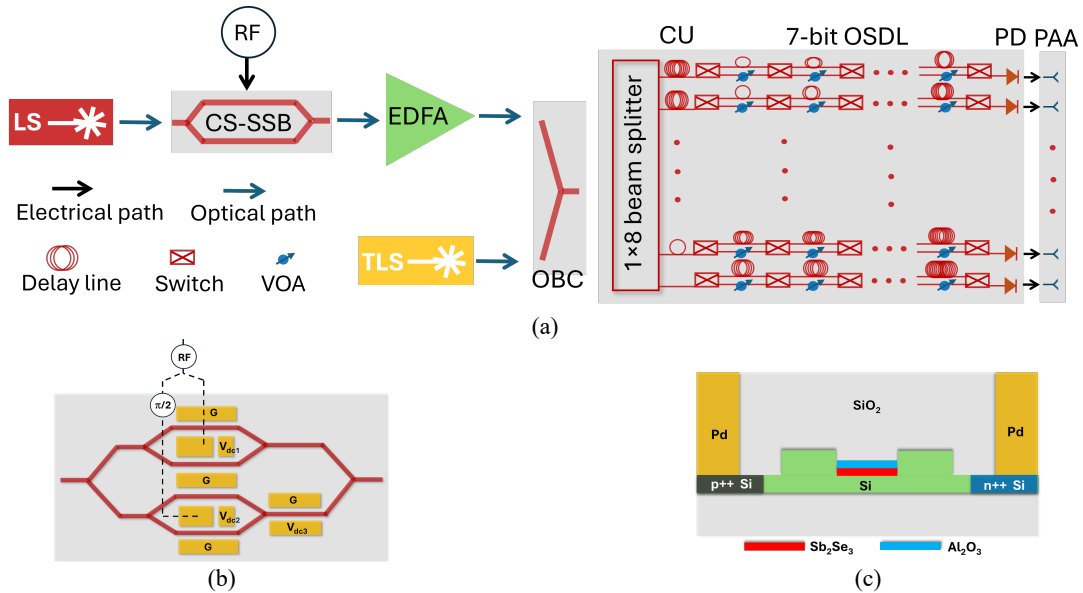


Fig.1 (a) Schematic of the proposed microwave photonic beamforming system. (b) Top view of the CS-SSB modulator. (c) Cross-sectional view of the PCM-aided switch with a symmetric-directional coupler.

The schematic of the proposed frequency-agile beamformer is illustrated in Fig.1(a). A narrowband laser source (LS), operating around the telecommunication wavelength of 1.55 μm , provides the optical carrier for the system. The RF baseband signal modulates the optical carrier through a carrier-suppressed single-sideband (CS-SSB) modulator based on cascaded Mach-Zehnder interferometers, as depicted in Fig.1(b). Depending on the phase imposed through $V_{\text{dc}3}$, the modulated optical power is concentrated either on the first-order upper or lower sideband only. The modulated signal is then amplified by an erbium-doped fiber amplifier (EDFA) and combined, through an optical beam combiner (OBC), with the optical signal generated by a narrow-band tunable laser source (TLS), which is also operating around 1.55 μm . The modulation scheme and the optical combining mechanism play a key role in dynamically controlling the transmitted RF frequency, as discussed later. The combined optical signal is subsequently fed to the optical beamforming network (OBFN), which consists sequentially of a 1×8 beamsplitter, delay compensating unit (CU), and a PCM-aided 7-bit OSDL unit. At the output of the OBFN, the optical signals are converted back into the RF signals through beating of the modulated upper/lower sideband and the tunable laser frequency at photodetectors (PDs). The RF signals generated by the PDs are then used to feed the antenna elements of the PAA.

Beam steering is controlled through the relative optical delays generated by the CU and 7-bit OSDL in a standard silicon-on-insulator (SOI) rib waveguide platform. For a given bit depth m , the delay introduced by the CU is scaled according to the antenna count n as $2^{(m-1)}(N - n)U$, where N is the total number of antenna elements being taken to be 8 and U is the basic delay unit given by,

$$2^{(m-1)}U = d \sin(\theta)/c \quad (1)$$

where d is the spacing between two adjacent antenna elements, chosen as half of the transmitted RF wavelength, c is the free-space light velocity and θ is the field of view (FOV), which is targeted to be $\pm 60^\circ$. For the given parameters and with a maximum RF frequency of 40 GHz, U is estimated to be 0.169 ps. Each 7-bit OSDL unit feeding an antenna element consists of 8 PCM-aided switches and 7 spiral delay lines. Each of the spiral delay paths is placed between two switches. The delay of each element is scaled with the antenna count n and bit depth m as $2^{(m-1)}nU$. The combined arrangement of CU and OSDL enables squint-free beam steering at both positive and negative pointing angles with a maximum steerable states of $2^7 = 128$ ^{6,8}. A variable optical attenuator (VOA), based on a silicon p-i-n diode is included in each reference arm between two switches to compensate for possible amplitude imbalances that may arise from fabrication imperfections. Unlike conventional PCM-integrated asymmetric directional couplers (DCs), the switching operation is realized using a compact symmetric DC, in which a thin layer of low-loss PCM is placed at the coupling gap and covered by a protective of Al_2O_3 layer. This configuration reduces the energy consumption of the symmetric DC switch compared with the previously adopted asymmetric one, as will be discussed in the following section. Among the available PCM candidates, Sb_2Se_3 is selected because of its nearly zero propagation loss in the telecommunication band and relatively fast crystallization dynamics. Its suitability for proposed beamformer has been discussed in detail in our recent work⁸. The cross-section of the PCM-aided switch is shown in Fig.1(c).

The directional coupler is integrated with a p-i-n heater to electrically induce the phase transition of the PCM layer. Palladium (Pd) is chosen for the metallic contacts because of its mechanical robustness and ability to withstand high temperatures. In numerical analyses, all the components are designed with the finite element method (FEM), whereas the system-level analysis is carried out using optical system designer software (OSDS). The far-field radiation pattern is estimated with the help of 1D array factor governed by^{5,8}

$$F(\theta) = \sum_{n=1}^8 A_n \exp\left(\frac{2\pi}{\lambda_{\text{tra}}} (n-1) d \sin\theta - \phi_n\right) \quad (2)$$

where, A_n , ϕ_n and λ_{tra} are the RF amplitude, phase, and wavelength at n^{th} antenna element, which has been collected from the oscilloscope viewer in OSDS. It should be noted that the numerical analysis is limited to the design of the PCM-aided switch and the frequency control unit only. The specifications of the remaining beamforming components, including the CU, delay units, and beam splitters, are taken from our previous work⁸ and incorporated into the system-level model.

RESULTS AND DISCUSSION

The OBFN chip is designed on an SOI platform using a silicon rib waveguide with a slab height of 100 nm and a waveguide height of 120 nm. The waveguide width of each arm in the symmetric-DC switch is set to 500 nm. Figure 2(a) shows the variation of the coupling length ratio at the amorphous to crystalline state of Sb_2Se_3 as a function of DC gap (G) for three

different PCM thicknesses. The horizontal line represents the values of length ratio at which the coupling length in the amorphous state is twice that in the crystalline state. Under this condition, complete power transfer to the cross port occurs in the amorphous state, whereas the through port is selected in the crystalline state. As shown in the figure, the required condition is met at smaller values of G as the PCM thickness increases. Since thinner PCM layers generally allow faster crystallization, an intermediate PCM thickness of 30 nm is selected, resulting in an estimated gap of 650 nm. The transmitted spectra at the cross and through ports in the amorphous and crystalline states are shown in Fig.2(b) and (c), respectively, for three different coupling lengths. For a coupling length of 62 μm , the insertion loss is approximately 0.14 dB and the switching extinction ratio exceeds 25 dB around 1.55 μm , reflecting good switching performance in both phases of Sb_2Se_3 . A 40 nm thick of Al_2O_3 layer is used as a protective layer to prevent any leakage of Sb_2Se_3 during amorphization.

The p-i-n heater is forward-biased by applying voltage pulses through the Pd electrodes. The doping concentration for both the p++ and n++ regions is 10^{20} cm^{-3} . The applied voltage pulses increase the temperature of the PCM embedded in the DC mainly through Joule heating. The temperature distribution across the switch cross-section is shown in Fig.3(a). The maximum temperature is reached at the center of the structure where the PCM layer is placed. Direct exposure of the PCM to this high-temperature region enables an energy-efficient phase transition of Sb_2Se_3 . The applied voltage pulses and the corresponding temperature variation with time are shown in Fig. 3(b) and Fig. 3(c), for amorphization and crystallization, respectively. The pulse duration is set to 100 ns for amorphization and 5 μs for crystallization.

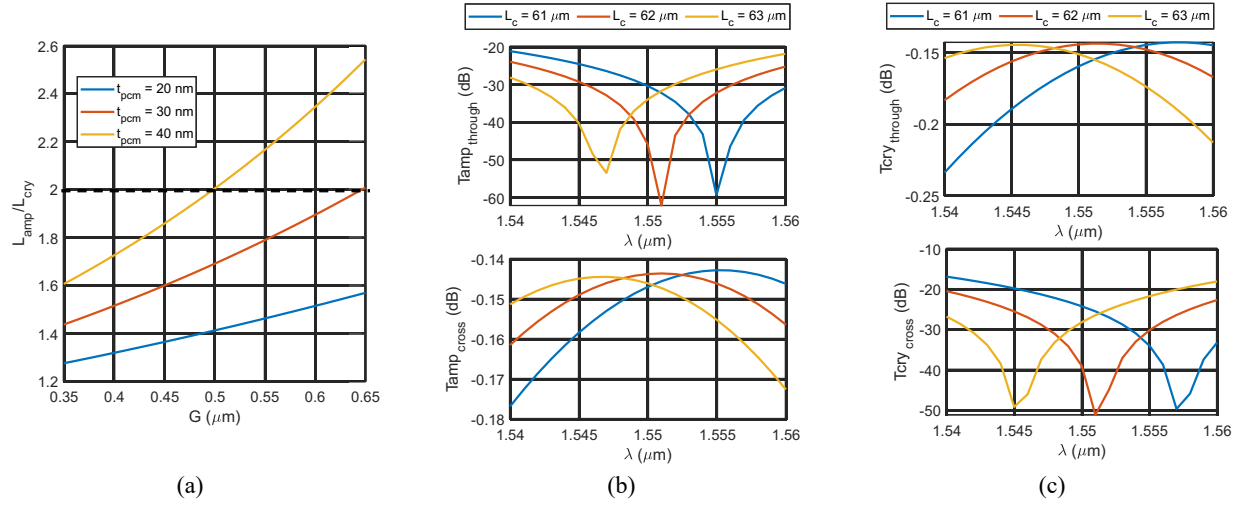


Fig.2 (a) Variation of the coupling length ratio at amorphous and crystalline states with the gap G for three different PCM thicknesses. Transmission spectrum at the through and cross ports in (b) the amorphous state (c) the crystalline state.

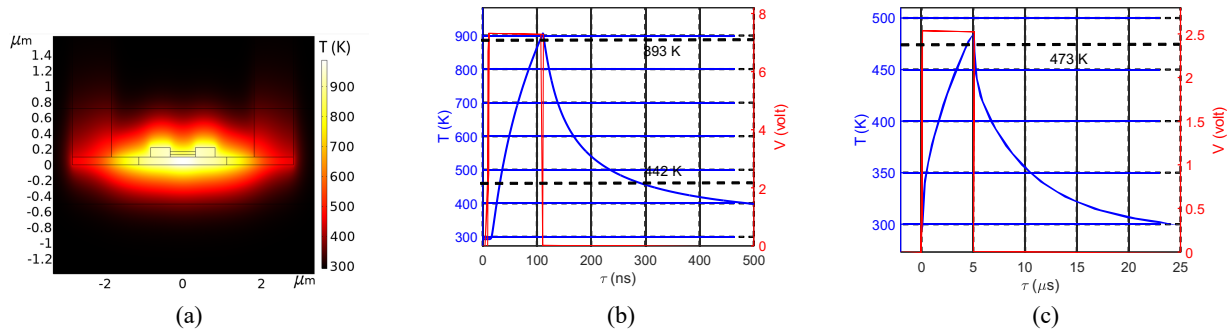


Fig.3 (a) Temperature profile at the trailing edge of the voltage pulse during amorphization. The voltage pulse and temperature variation with time during (a) amorphization (b) crystallization.

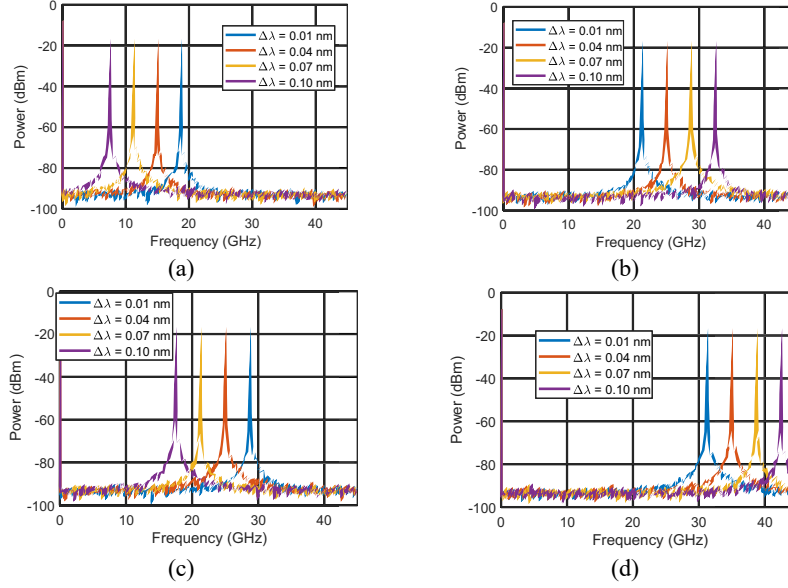


Fig.4 The transmission RF frequencies generated through the PDs with (a) $f_b = 20$ GHz, $\phi_a = \pi/2$ (b) $f_b = 20$ GHz, $\phi_a = -\pi/2$ (c) $f_b = 30$ GHz, $\phi_a = \pi/2$ (d) $f_b = 30$ GHz, $\phi_a = -\pi/2$ for four different tuned wavelengths through TLS.

Figure 3(b) and (3(c)) show that applied voltages of 7.3 volt and 2.53 volt allow the PCM temperature to exceed the melting and crystallization temperatures of Sb_2Se_3 , taken as 893 K and 473 K, respectively. The 100 ns pulse used for amorphization produces a quenching rate of 2.08×10^9 K/s, which is sufficient to achieve amorphization of Sb_2Se_3 ¹⁰. The energy consumption for crystallization and amorphization is estimated to be 8.7 nJ and 3.2 nJ, respectively, compared with 10 nJ and 3.3 nJ obtained for the previously reported asymmetric DC-based switch⁸. The improved energy efficiency is attributed to the more favorable position of the PCM within the peak-temperature region. In the asymmetric DC, in contrast, the PCM layer is located on top of only one waveguide arm. The numerical analysis is performed using an FEM-based Multiphysics model including semiconductor and heat transfer in solid physics. The two side boundaries and lower boundary are placed 100 μm away from the heat source and maintained at room temperature to mimic the real thermal environment of the device. A convective boundary condition is applied at the uppermost boundary⁸.

Before analyzing the complete system, the frequency control unit, consisting of two laser sources, a lithium niobate modulator, and a Ge photodiode, is investigated separately in OSDS. The operating principle of the CS-SSB modulator can be understood with reference to Fig.1(b). The applied dc voltage V_{dc1} and V_{dc2} bias the two MZIs at π , while the baseband RF signal at frequency f_b drives them with a constant phase difference of $\pi/2$. The peak-to-peak modulating voltage (V_{pp}) is set to $1.17V_\pi$ such that most of the modulated power is concentrated in the first order modulating sideband ($f_c \pm f_b$) while the optical carrier is completely suppressed. The two terms V_π and f_c represent the half-wave voltage and optical carrier frequency generated by LS, respectively. Modulator parameters such as V_π and insertion loss are taken from commercially available data¹¹. The dc voltage V_{dc3} introduces an additional phase difference between the two MZIs to hinge the modulating power only in one sideband. The power stays only in the upper sideband for an applied phase (ϕ_a) of $\pi/2$ and in the lower sideband for $\phi_a = -\pi/2$. The selected sideband is heterodyned at the PD with the TLS operating at a tunable frequency f_t , generating the transmitted RF signal at $f_r = |f_t - (f_c \pm f_b)|$. The transmitted spectra for two baseband frequencies, $f_b = 20$ GHz and $f_b = 30$ GHz, are shown in Fig. 4(a-d) for $\phi_a = \pi/2$ and $-\pi/2$ and for four different wavelength shifts ($\Delta\lambda$) through the TLS from the reference wavelength 1.55 μm set by the LS. The results clearly show that the transmitted RF signal can be frequency-upshifted ($\phi_a = -\pi/2$) or downshifted ($\phi_a = \pi/2$) at different values by controlling the lasing wavelength of the TLS for any received baseband signal. This mechanism therefore enables dynamic adjustment of the transmitted frequency for different received baseband signals. In the OSDS simulations, the bandwidth and power of the two laser sources are taken to be 10 kHz and 15 dBm, while the PD responsivity is set to 0.8 A/W.

The full system-level analysis is then performed in OSDS by combining the designed switch and frequency-shifting elements with the remaining beam-forming components described in our recent work⁸. The OBFN is placed between the frequency converter stage and photodetector array and is implemented in the system-level model through the transfer

matrix method⁸. This approach reduces the simulation complexity while maintaining the required accuracy. Figure 5(a) and Fig. 5(b) show the calculated steerable far-field radiation patterns at different transmitted frequencies for two given baseband signals at $f_b = 20$ GHz and 30 GHz, respectively. The beamformer supports 128 steerable angles, each of which is represented by the state number B. Both figures include five different angles denoted by B (bit configuration) = 0 (0000000), 32 (0100000), 64 (1000000), 96 (1100000), 127 (1111111). The results demonstrate squint-free beam-steering at arbitrary transmitted frequencies for both considered baseband signals. The resulting FOV ranges from -59.8° to 58.4° , with an angular resolution of 0.92° . For clarity, only two upshifted and two downshifted frequencies are shown for $f_b = 20$ GHz and 30 GHz. The total energy consumption of OBFN is estimated to be $12.1 \mu\text{J}$, which is even lower than $13.5 \mu\text{J}$ reported for our previous beamformer⁸, thanks mainly to the improved positioning of the PCM. In addition, the nonvolatile nature of the PCM also halves the total switching operations as compared to traditional means of volatile programmability and plays a crucial role in curbing energy consumption.

The combination of low-energy beam steering and dynamically adjustable transmission frequency demonstrates the potential of the proposed architecture for next-generation wireless and space communication systems. Future work will address phase-locking strategies for the two laser sources to improve the coherence and stability of the generated RF signal, as well as the extension of the proposed concept to two-dimensional beamforming.

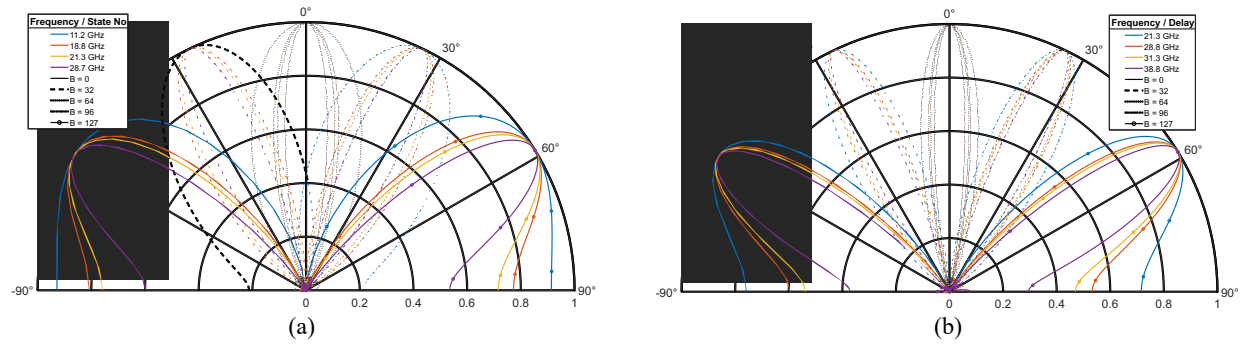


Fig.5 The far-field radiation pattern for (a) 20 GHz and (b) 30 GHz at two different upshifted and downshifted frequencies and five different beam steering angles. The frequencies and state numbers are respectively denoted by different colors and line shapes.

REFERENCES

1. Y. Niu et al., "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges," *Wireless Networks* **21**(8), 2657–2676 (2015) [doi:10.1007/s11276-015-0942-z].
2. G. Brunetti et al., "Innovative optical beam steering network for sub-meter satellite SAR," *Opt. Lasers Eng.* **198**, 109520 (2026) [doi:10.1016/j.optlaseng.2025.109520].
3. S. Shi et al., "Integrated Optical Tunable Delay Line and Microwave Photonic Beamforming Chip: A Review," *Laser Photon. Rev.* **19**(7), 2400663, John Wiley & Sons, Ltd (2025) [doi:10.1002/lpor.202400663].
4. G. Brunetti et al., "Design of an ultra-compact graphene-based integrated microphotonic tunable delay line," *Opt. Express* **26**(4), 4593–4604, Optica Publishing Group (2018) [doi:10.1364/OE.26.004593].
5. C. Zhu et al., "Silicon integrated microwave photonic beamformer," *Optica* **7**(9), 1162–1170, Optica Publishing Group (2020) [doi:10.1364/OPTICA.391521].
6. P. Martinez-Carrasco et al., "Ultrabroadband high-resolution silicon RF-photonic beamformer," *Nat. Commun.* **15**(1), 1433 (2024) [doi:10.1038/s41467-024-45743-9].
7. N. Saha, G. Brunetti, and C. Ciminelli, "Highly efficient Phase Change Material assisted Reconfigurable Optical Delay Line based on Cascaded Coupled-Resonator Optical Waveguides," *Journal of Lightwave Technology*, **43** (17), 8274–8285 (2025) [doi:10.1109/JLT.2025.3583068].
8. N. Saha, G. Brunetti, and C. Ciminelli, "A compact SOI-based high-resolution broadband RF beamformer with phase change material aided programmability," *Journal of Physics: Photonics* **8**(2), 025044, IOP Publishing (2026) [doi:10.1088/2515-7647/ae6ffd].
9. M. Delaney et al., "A New Family of Ultralow Loss Reversible Phase-Change Materials for Photonic Integrated Circuits: Sb₂S₃ and Sb₂Se₃," *Adv. Funct. Mater.* **30**(36), 2002447, John Wiley & Sons, Ltd (2020) [doi: 10.1002/adfm.202002447].

10. J. R. Erickson et al., “Designing fast and efficient electrically driven phase change photonics using foundry compatible waveguide-integrated microheaters,” *Opt. Express* **30**(8), 13673–13689, Optica Publishing Group (2022) [doi:10.1364/OE.446984].
11. “Lithium Niobate Electro-Optic Modulators, Fiber-Coupled (1260 nm - 1625 nm),” <https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=3918>.