Integrated Antenna Modules for Photonic RF Sensing and Communications

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Abstract: In this paper we present some recent advancements in antenna/photonic device integration for radio? over fiber applications. In our direct integration investigations we divide our approach based on frequency bands; below 6 GHz and above 26 GHz (Ka-band) to be consistent with such applications as present day 5G and 5G+ systems.

1. Introduction

Future wireless communication networks require larger effective bandwidths than previous generations to meet the ever-increasing demand for high data rate applications such as augmented/virtual reality. This can be achieved using aggregated channels in the lower microwave spectrum (less than 6 GHz), commonly referred to as spectral slicing or utilizing the large amount of available spectrum in the millimeter-wave (mm-wave) frequency bands. Needless to say, when discussing wide relative RF bandwidths (multiple octaves) or high wireless frequencies (> 26 GHz) and small mobile cell structures (pico-cells, etc), radio over fiber (RoF) is often proposed as a logical, efficient technology that can readily meet the overall system requirements [1]. Although mm-wave 5G is not yet widely deployed and is now being considered for 5G+ or even 6G, it would be very difficult to achieve the goals of future wireless networks (including very low latency and high efficiency) without incorporating RoF technology somewhere in the mm-wave system. In addition, the development of concepts that enable the efficient integration of antenna, RF and optical functionalities will play an important role in the realization of these future networks. Recently there has been some excellent progress in this area attempting to develop modules primarily in Silicon to potentially yield low cost, efficient multi-functional sub-systems in both the optical and RF/antenna domains [2, 3]. Importantly, these approaches use fabrication techniques compatible with high volume, low cost production. Over the years we have investigated how to integrate antennas directly with photonic components (transmitters and receivers) to yield efficient solutions [4]. The techniques developed are also directly compatible with Silicon fabrication procedures.

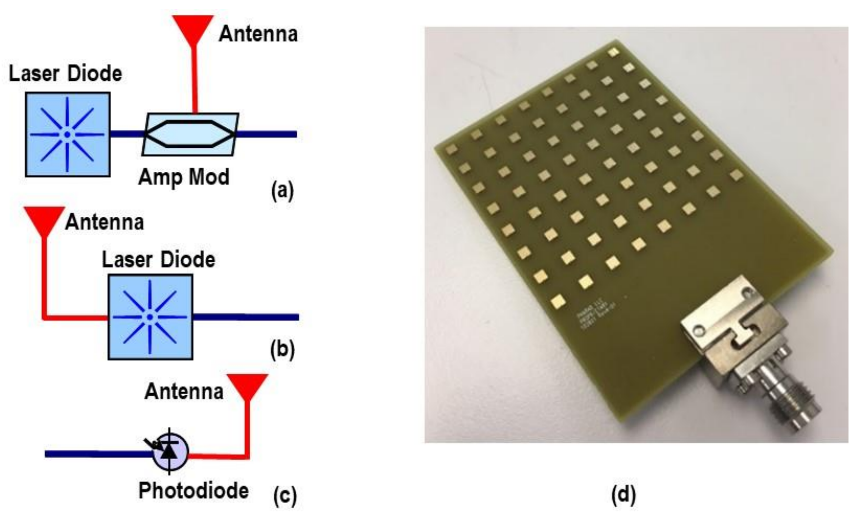


Fig. 1. Direct integration configurations investigated (a) – (c) and example of Silicon compatible antenna (d).

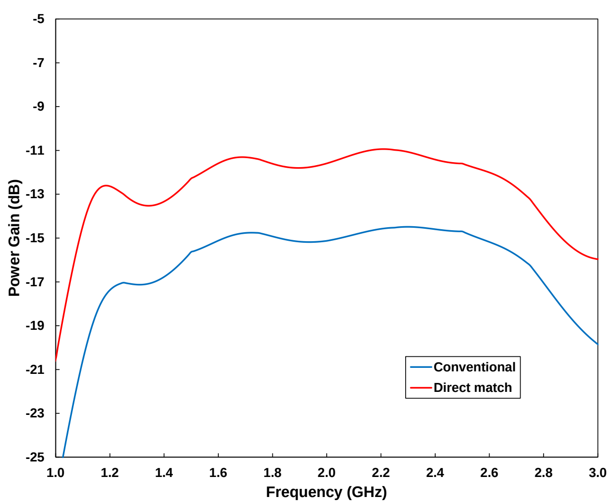
In this paper we summarize our most recent investigations developing integrated antenna/photonic modules which focus on matching the antennas directly to the RF impedance response of the photonic devices while ensuring the radiation efficiency of the structure is not compromised. The work is divided into two frequency bands, below 6

GHz and at mm-wave frequencies, similar to the 5G low and high frequency bands under consideration. Since the RF radiation requirements of the antenna for these two bands is significantly different, the level of integration required between the radiating structure and the photonic devices is also not the same. At lower frequencies banded sectorized radiating structures, similar to those used in previous cellular generations, are being utilized. For mm-wave bands and higher, phased array radiators (or equivalent) are required to achieve the high data rates to multiple users. Figs. 1 (a) – (c) show generalized schematics of what we are attempting, where the antenna is directly connected to the relevant photonic device; the red line represents the RF path and the purple line depicts the optical path. In the receive mode, the antenna is connected to a photodiode (PD) whereas for the transmit mode, the antenna is connected to either a laser diode (LD) for frequencies below 6 GHz or an optical amplitude modulator. Fig. 1 (d) shows a photograph of a 'Silicon' compatible array configuration we have previously developed for 5G+ applications [5].

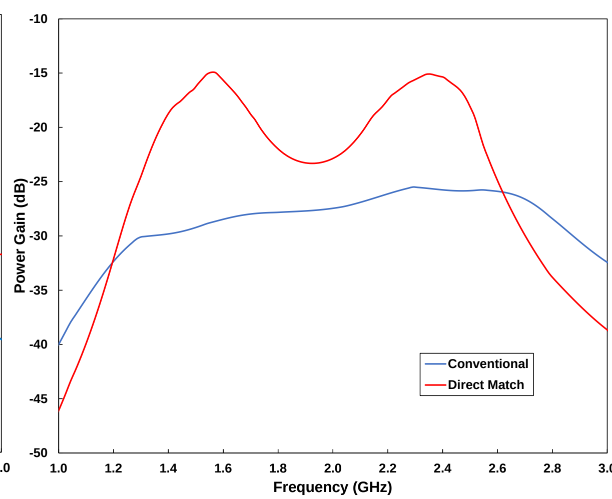
2. Lower Frequency Integration

For frequencies less than 6 GHz we consider integrating patch-based antennas with directly modulated optical links. Aperture Stacked Patches (ASPs) are used as the radiator [6] due to their inherent wideband nature, excellent polarization isolation, as well as ease of integration with RF and optical active devices. In this investigation, we use equivalent RF circuit models for the laser diodes [7] and photodetectors [8] and a 2-port representation of the antenna [4] to determine the overall link efficiency. In the 2-port representation of the antenna the impedance response, radiation efficiency and gain of the antenna are all taken into consideration.

Fig. 2 (a) shows the link efficiency of an ASP designed for operation over 1.5 – 2.5 GHz (covering several 5G bands) when integrated with a commercial LD. Here the antenna is designed to have a VSWR (Voltage Standing Wave Ratio) < 2:1 over this frequency range (normalized to 50 Ω) and its feed layer composition is Silicon-based. The LD has an internal resistor (25 Ω) to help match its input. Also shown in this plot in red is the link efficiency when the matching resistor of the LD is removed and the antenna is designed to conjugately match the response of the LD over 1.5 – 2.5 GHz. As can be seen, there is significant improvement in the efficiency performance when directly matching the antenna to the LD. A couple of important aspects should be noted here. Firstly the 'radiating layers' of the antenna are low loss laminates and so the efficiency of the ASP is high (>85 %) and the gain is approximately 7 dBi across the band of operation. Secondly, because we are ensuring the antenna has a high radiation efficiency, maximum power gain is achieved. Finally, the undulation in the response over the band of operation is due to impedance variations of both the optical device and the antenna as a function of frequency.



(a)



(b)

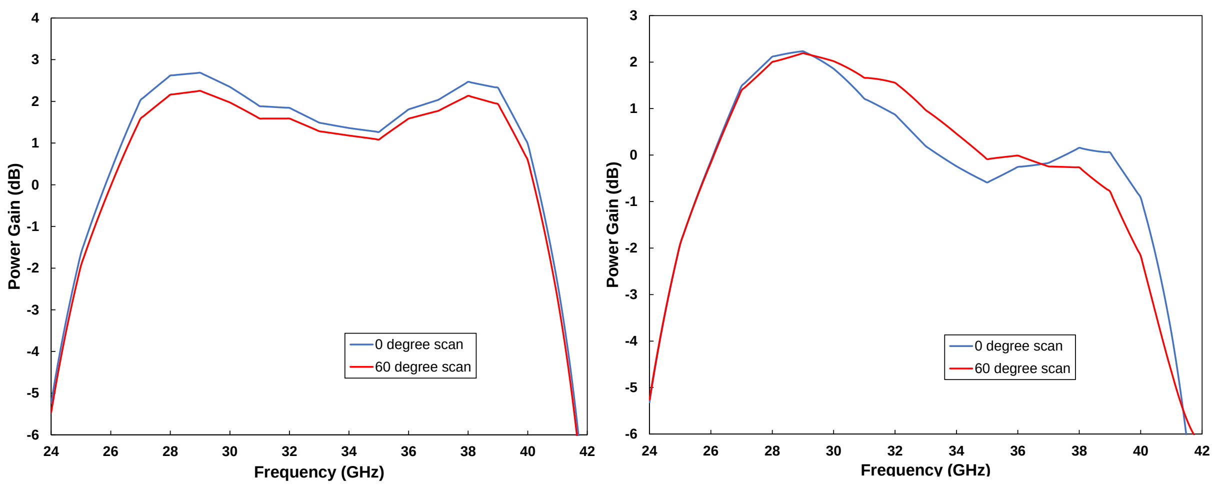
Fig. 2. Predicted link gain for direct integration of ASP with (a) Laser Diode; and (b) Photodiode.

Fig. 2 (b) shows the link performance when integrating the 1.5 – 2.5 GHz ASP to a PD. Two cases are also considered here, firstly when the antenna is designed for 50 Ω and the PD has a matching resistor (the conventional matching scenario shown in blue) and when the antenna is optimized to match directly to the PD that has the matching resistor removed. Once again, improvement in performance (by greater than 6 dB) has been achieved across the band of operation. The undulation in the direct matching response that can be seen is due to the challenge of keeping the impedance locus of the antenna 'tight' over the entire band of operation.

3. Millimeter-wave Integration

As discussed earlier, mm-waves will undoubtedly play a major role in future cellular networks. With the exception of fixed wireless access (FWA) communications, some type of phased array variations will be required at these frequencies to meet the radiation requirements for cellular links. Requirements for these mm-wave antennas include being able to operate efficiently over a large bandwidth, for example the entire Ka-band, reasonable gain to compensate for the free-space loss at these frequencies as well as the ability to scan to large angles (± 60°). Realizing a mm-wave antenna that satisfies this combination of requirements is especially challenging when trying to develop a solution that is also compatible with silicon integration procedures. Recently we proposed a variation of the probe-fed stacked patch antenna that can meet these goals [9]. The antenna is well matched over the entire Ka-band and can be scanned to beyond ± 60° in all planes. It also features good gain/efficiency over the Ka-band as well as scanning ranges; a 16 × 16 element configuration has a gain greater than 24 dBi across the band.

For the integration investigation we considered the integration of each unit cell of the array to a UTC photodiode [8] for the transmit mode and a Lithium Niobate balanced modulator for the receive mode. Fig. 3 (a) shows the predicted link performance (effectively the active gain) of each unit cell of a large array of these antenna elements when the impedance response of the radiator has been matched to the modulator and Fig. 3 (b) when matched to the photodiode at broadside (0° scanning). Also shown in each plot are the results for when the array is scanned to 60 degrees. The overall responses are fairly similar because the antenna element in this array is electrically small and so its impedance does not vary greatly with scan angle.



(a) (b)

Fig. 3. Predicted link gain for integration of mm-wave antenna array with (a) optical modulator; and (b) Photodiode

3. References

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