Photonic integrated circuits for radar beam control

Photonic integrated circuits have the potential to reduce the volume and weight of optical beamforming networks for phased-array radar antennae by more than one order of magnitude, and will drastically reduce packaging and interconnection costs by integrating subcircuits, consisting of many components, on a single chip. Most work on optical beamforming networks reported so far has been based on discrete optical components.[1,2] Here we describe a first realization of an integrated optical chip with dimensions less than 1×1 cm^2 which can control amplitude and phase of 16 antenna elements.

Operation principle.

Phase and amplitude of the antenna elements in a phased-array radar antenna can be controlled using phase and amplitude controllers. Using a coherent detection scheme, phase and amplitude of an optical signal can be directly transferred to a microwave signal. This is done by mixing the original optical signal with a second one that is frequency-locked to the first with a frequency difference Δf equaling the required microwave frequency (see Figure 1a). In this way, modulation of phase and amplitude of a microwave signal can be performed using optical phase and amplitude modulators. This scheme has two advantages over rf-electronic phase and amplitude control: optical controllers are much smaller that electronic ones, and the bandwidth of the controllers is huge. With proper rf-photodetectors, the phase and amplitude of the microwave signal can be accurately controlled from a few MHz up to more than 100 GHz. A disadvantage of the coherent scheme are the requirements on the linewidth of the optical sources: the optical amplitude and phase noise are directly transferred to the microwave signal.

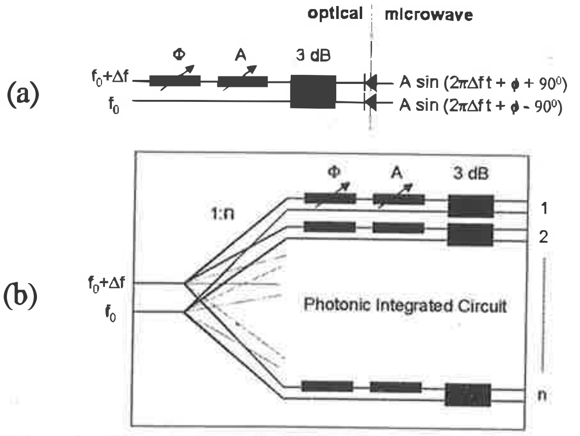

Figure 1. a) Phase and amplitude of a microwave signal using optical modulators and coherent optical detection. b) Optical circuit for controlling phase and amplitude of a number of antenna elements.

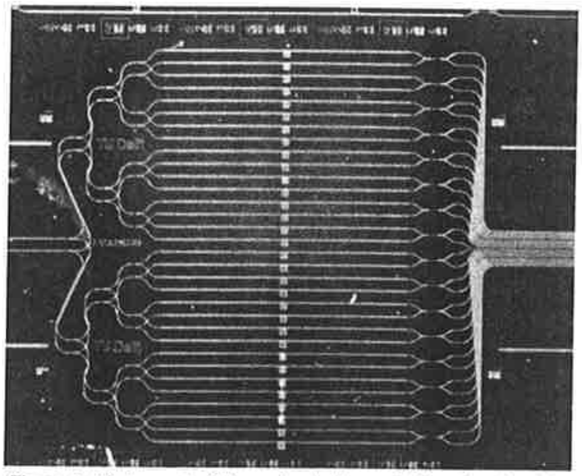

Figure 2. Photograph of the optical chip containing the circuit for controlling 16 antenna elements according to Figure 1b. Chip dimensions are 8×8.5 mm².

Design

Figure 2 shows a semiconductor-based optical chip containing the control circuit for 16 antenna elements as depicted in Figure 1b). The chip has been realized with InGaAsP waveguides on InP substrates. It operates at 1.55 μm: the wavelength most common in broadband optical communication links. The whole chip measures only 8×8.5 mm^2. At the left side of the chip the two interspersed 1×16 power splitting circuits are visible. They have been realized as a tree of 15 1×2 splitters cascaded in four stages. For the splitters, we used MMI-couplers: a compact and fabrication-tolerant coupler type with approximately 0.5 dB insertion loss and a length of only 400 mm. The splitters are connected with 2-μm wide waveguides which have curvature radius of 250 μm without excessive radiation loss.

The InGaAsP wave-guides have been made electro-refractive by growing them onto an n-type InP substrate and covering them with a p-type InP cladding layer. By reverse biasing the so-formed pin-diode, an electrical field is created across the waveguide layer. This changes the refractive index of the waveguide material and thus the phase of the optical signal propagating through the waveguide. The central part of the chip shows the modulator sections (the parallel waveguide section: the rectangles in the center are bondpads for applying the control voltage). The modulators can be used both as phase (electro-refraction) and amplitude (electro-absorption) modulators: below 10 V the absorption is low, beyond 10 V it rapidly increases.

Experimental results

The fabricated chip has been characterized by coupling light from a single laser into both input ports and measuring both the insertion loss and the uniformity of the 16 channels, and the phase and amplitude response to an applied modulator voltage.[3]

Insertion loss. For the whole chip we measured an excess loss of 13 dB which is composed as follows: 1 dB waveguide propagation loss, 5 dB for the 1×16 splitters, 1 dB for the waveguide crossings, 1 dB for the modulators and approximately 5 dB because of some optical damage in the input section of the circuit. We expect that, with improved processing, the total on-chip circuit loss can be as low as 5 dB. The uniformity of the 16 output channels was within ±1.5 dB.

Phase and amplitude modulation response. With a voltage below 5 V, 360° of phase shift can be obtained using the electrodes in both arms. For higher voltages, the absorption rapidly increases up to 17 dB at 20 V. Phase and amplitude can be controlled by using the electrodes on the upper and lower waveguide for each channel simultaneously. To arrive at a predefined value for amplitude and phase, first the attenuation has to be set by applying the proper voltage to both electrodes. Next the phase can be set by varying the voltages on both electrodes in an opposite way around the setting voltage.

Photonic integration can greatly reduce the weight and volume of beam-forming networks for phased-array radar antennae, as well as offering a huge bandwidth. The main challenge is the development of spectrally pure optical sources.

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