DESIGN OF A RING RESONATOR-BASED OPTICAL BEAM FORMING NETWORK FOR PHASED ARRAY RECEIVE ANTENNAS

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ABSTRACT

A novel squint-free ring resonator-based optical beam forming network (OBFN) for phased array antennas (PAA) is proposed. It is intended to provide broadband connectivity to airborne platforms via geostationary satellites. In this paper, we present the design of the OBFN and its control system. Our goal is to deliver large bandwidth K_u-band connectivity between antennas, mount conformal to the airplane fuselage and on a geostationary satellite, respectively. This way it would be possible to bring live DVB-S television to airplane passengers.

In this paper, we present recent research conducted on a 4 × 1 ring resonator-based OBFN test set-up. This OBFN has four optical input ports and one optical output port. It is tuned to provide the desired signal combination with optimal constructive interference between the modulated input signals from the PAA. Therefore, combining circuitry and delay elements are required.

The OBFN is tuned by electrically heating tunable true time delay (TTD) elements. These are built using optical ring resonators (ORRs). By cascading multiple ORRs with different resonance frequencies, it is possible to create a TTD with a large bandwidth.

Optical beam forming is used because it provides advantages over traditional beam forming methods. These advantages are: large bandwidth, EMI resistance, and, when integrated onto a single chip, compactness and low costs.

The OBFN is created using planar optical waveguide technology and consists of the following building blocks: waveguides, Mach-Zehnder interferometers, (MZIs) couplers and ORRs.

The tuning of the OBFN is done by an electronic control system using a microcontroller. Communication with a PC is possible using USB.

To our knowledge, this is the first integrated ORR-based OBFN circuit for PAA satellite reception.

INTRODUCTION

Enhanced aircraft communications require large bandwidth connectivity. Conventional antennas however, have disadvantages when mounted on an aircraft fuselage, such as increased drag and maintenance.

At the same time, optical technology is gaining its preference in wireless transmission systems. An application of this is an optical beam forming system for PAAs. The optical technology we are currently investigating is intended to deliver large bandwidth (i.e., 2 GHz) K_u-band connectivity between antennas, mount conformal to the airplane fuselage and on a geostationary satellite, respectively. This way it would be possible to bring DVB-S television to airplane passengers.

We believe optical beam forming is a good candidate for correlating RF signals in such a system, because it provides advantages over traditional beam forming methods. Such advantages are: large instantaneous bandwidth, EMI resistance, and, when integrated onto a single chip, compactness, low weight and low costs.

Previously, Boeing provided a large bandwidth internet connection for a short time in its Connexion by Boeing (CBB) service via commercial geostationary K_u-band satellite links. Lufthansa installed this service as *SkyAccess* on some of its aircraft. In 2006 however, Boeing stopped the CBB service, because the market for this system did not turn out as aspected. Currently, no large bandwidth K_u-band services are available on airborne platforms to a large public. For example [1] shows however that there is a demand for services requiring these connections.

This paper proceeds as follows. First, a short system overview is given. In the following Section, the system principles are explained: the system overview, the OBFN and its control system are explained. Then, delay measurement results are presented. Finally, conclusions and some remarks are formulated.

SYSTEM PRINCIPLES

System Overview

Our proposed system is shown in Fig. 1. For a typical receive scenario, it consist of the parts shown there. The Antenna Elements (AEs) receive satellite signals. These are intensity modulated onto an optical carrier (E/O block) and fed into the OBFN, where they are delayed and combined. This results in one strong optical signal, which is then reconverted to the electrical domain using a photodiode detector (O/E block). Afterwards, it can be detected using for example a set top box. This system is developed in the FlySmart project, in which a consortium of the Dutch National Aerospace Laboratory NLR, The University of Twente, Lionix BV and Cyner Substrates cooperate.

Optical Beam Forming Network

The optical chip in this system is manufactured using planar optical waveguide technology. It consists of the following building blocks: waveguides, MZIs, couplers and ORRs. ORRs are chosen because they provide true time delay when cascaded, so beam squinting will not occur. The building blocks are combined to form an OBFN. A 1 × 4 OBFN for a transmitter phased array is shown in Fig. 2(a). It employs a binary tree topology, which has an efficient layout with respect to the required number of ORRs. This puts restrictions on tuning freedom compared to a parallel topology, reduces tuning complexity [2]. An ORR consists of a straight waveguide and a circular waveguide coupled to it. It has a periodic group delay response, representing the effective time delay to the modulated RF signal. The group delay is mathematically expressed by

$$\tau_g(f) = \frac{\kappa T}{2 - \kappa - 2\sqrt{1-\kappa}\cos(2\pi f T + \phi)} \tag{1}$$

It depends on the round trip time T, the power coupling coefficient κ and additional round-trip phase shift of the ring ϕ. It is possible to control both the phase shift ϕ and power coupling coefficient κ, thereby tuning the ORR peak value delay and resonance frequency. There is a trade off between peak delay and bandwidth. Therefore it is useful to cascade ORRs, creating broadband delay elements. This yields a group delay response that is simply the sum of the individual ORR responses. Fig. 2(b) clarifies this: the group delay response of three cascaded rings (shown in the inset) is the sum of the three individual responses, marked with the three dashed lines. As the resonance frequencies of the ORRs gets closer, the ripple becomes smaller. The group delay then becomes more flat, but at the cost of a smaller bandwidth [3].

In our system, the OBFN is used to realign the individual AE signals, in order to combine them with maximal constructive interference. The output of a single laser is split, after which each AE signal is modulated using filter-based SSB-SC modulation, as discussed in [4].

The optical chip is tuned thermo-optically by electrically heating chromium resistors on it. As a consequence, the optical waveguide heats up and its refractive index changes. This allows for tuning of the resonance frequencies, delay tuning, and splitting ratios. The tuning is performed by a control system, as discussed in the next Subsection.

Control System

To perform the tuning of the optical chip, a flexible control system has been designed and implemented. It is based on a microcontroller, operating one or more D/A converters. The D/A converter outputs are amplified, to provide the voltages necessary to heat the resistors on the optical chip.

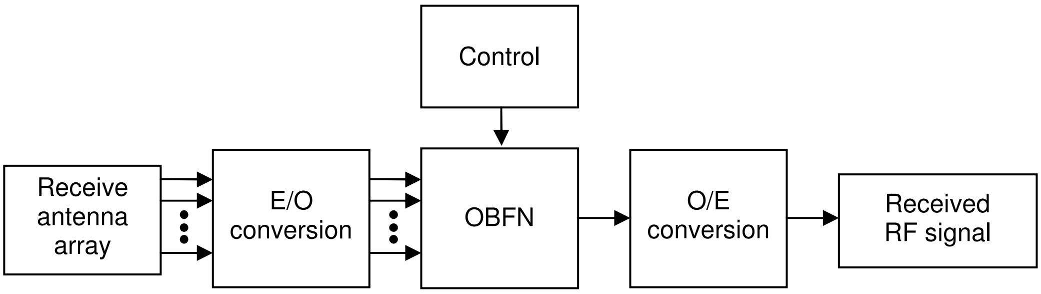
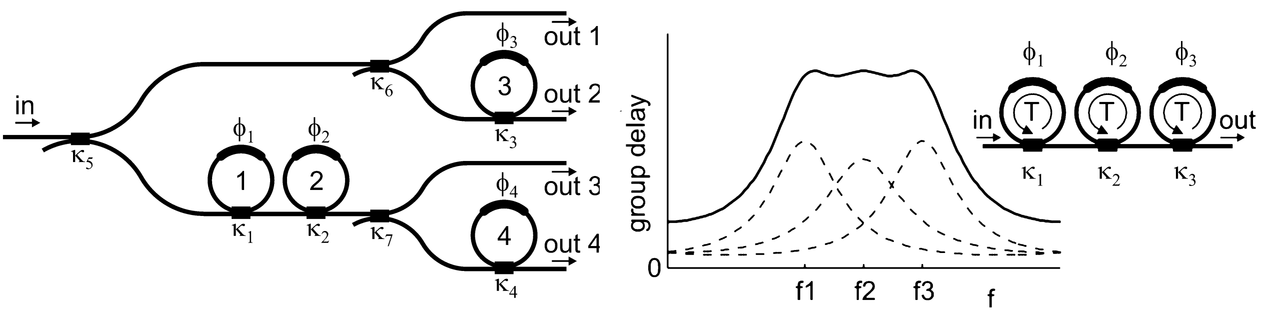


Fig.1. System overview of the optical beam forming system for phased array receive antennas.



(a) (b)

Fig.2. (a): 1 × 4 OBFN for a transmitter phased array, consisting of 4 ORRs.
(b): Theoretical group delay response of three cascaded ORRs. The solid line represents the total delay response, which is the sum of the group delay responses of the individual sections shown by the dashed lines. Inset: a cascade of three ORRs with power coupling coefiecients κ_i, round-trip delay T and additional round-trip phase shifts φ_i.

The layout of the control system is shown in Fig. 3. The ARM7 microcontroller runs its control software stored in flash memory. An LCD display is used to display some status information. The dedicated D/A converter and amplifiers are combined on a printed circuit board (PCB) and consist of 32 14-bit channels each. The D/A converter is connected to the microcontroller using Serial Peripheral Interface (SPI), allowing tuning of larger optical systems in the future. Storage is provided in a nonvolatile ferroelectric RAM (FRAM) to store and recall tuning settings. The control system is able to communicate with a PC using USB, via the universal asynchronous transceiver and transmitter (UART) of the microcontroller. It may however operate in standalone mode as well.

MEASUREMENT RESULTS

In Fig. 4, measurement results of group delay responses of an actual 1 × 4 OBFN chip are given. The rings are tuned, such that a flat group delay spectrum is obtained over a signal bandwidth of roughly 3.75 GHz. The largest delay value is approximately 1.3 ns (corresponding to 39 cm in air). The maximum ripple is about 0.05 ns. The measurements show that a sufficient tuning range can be generated for satellite TV communication (10.7-12.75 GHz). Like delay measurements presented in [5], these measurements are conducted using the phase shift approach, by means of a network analyzer.

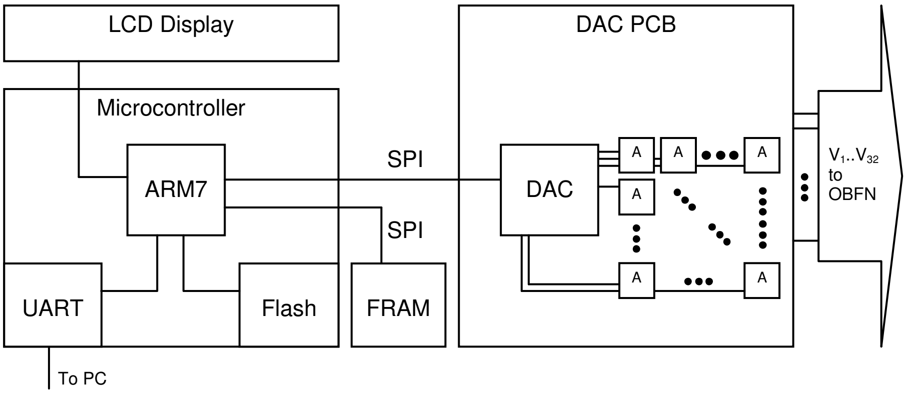


Fig. 3. Architecture of the control system. In the left part, the microcontroller is shown, with a connection to a display and a PC via its UART . Flash memory is used for the controlling software storage. A DAC PCB is shown on the right, connected to the microcontroller using SPI. It consists of a 32-channel DAC and an amplifier for each channel; the amplifer outputs go to the OBFN. For storage of tuning parameters, an FRAM is used.

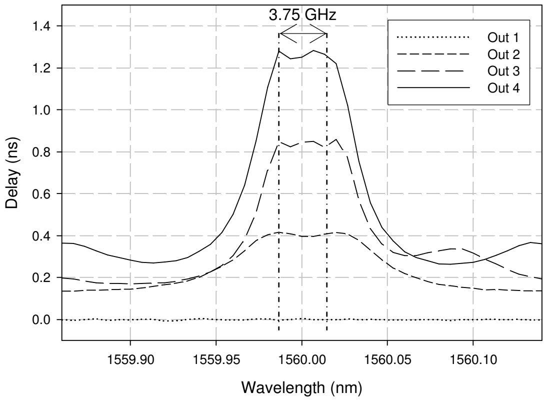


Fig. 4. Measured group delay responses at the 4 outputs of a 1 × 4 OBFN.

CONCLUSIONS AND REMARKS

In this paper, we presented a novel squint-free ring resonator-based optical beam forming system for phased array receive antennas. The system discussed is intended to deliver K_u-band connectivity between a satellite, and an antenna mount on an airplane. We presented a system design for a phased array antenna receive system, its OBFN, and the control subsystem. The OBFN consists of a continuously tunable delay network on a single optical chip, where ring resonators are used as tunable delay elements. The control system is a microcontroller based PCB. It actuates one or more 32-channel 14-bit D/A-converters, whose outputs provide voltages to tune the OBFN. To our knowledge, this is the first integrated ORR-based OBFN circuit for PAA satellite reception.

Measurements prove that the system is capable to use as a broadband beamformer. However, for an actual demonstrator, that will be built within the FlySmart project, further integration of system parts still needs to be carried out. This demonstrator aims at showing the broadband characteristics of the proposed system, beamforming, and the verification of tuning algorithms.

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