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Thermally tuned optical fiber for true time delay generation

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Abstract

A new technique for generating a continuous range of true time delay values is introduced. Heating optical fiber in order to change the effective index of the guided mode produces time delays. A 45-m section of single-mode silica fiber is demonstrated to produce a continuous range of time delay values from 0 to 211 ps over a temperature tuning range of 50°C (30–80°C). A thermal time delay factor is introduced and found to be 0.096 ps/m°C for Corning LEAF fiber. A 7.66-m section of multimode Lucina polymer fiber is demonstrated to produce a range of time delay values from 0 to 32 ps over a temperature tuning range of 30°C (30–60°C). The thermal time delay factor for this fiber is −0.1427 ps/m°C.
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Keywords: Optical fiber; Phased array antenna; True time delay

1. Introduction

It is generally expected that future phased array antennas (PAA) will be designed to operate across ultra-wide bandwidths. It will be necessary to use true time delay (TTD) steering techniques rather than phase delay techniques in order to meet these large bandwidth requirements and avoid beam squint. Optical TTD systems have many advantages over electrical TTD systems including immunity to electromagnetic interference, reduced system size and weight, and non-dispersive behavior over the large radio frequency and microwave bandwidths in which most PAA systems operate.

Numerous optical TTD generation techniques for phased array systems have been demonstrated. These include waveguide hologram-based tunable delays [1–3], fiber and waveguide delay lines with optical switches [4–7], chirped fiber gratings [8], and wavelength tunable dispersive delay lines [9,10]. However, these techniques have disadvantages such as limited total time delay, discrete time delay values rather than continuously tunable time delay, and high loss.

In order to steer a large bandwidth phased array antenna beam anywhere within the typical ±45° angle of operation, a continuously tunable time delay generation method is needed with a sufficiently large maximum time delay value and low loss. Fig. 1 shows the time delay requirements for a 4 × 4 subarray of a PAA with ±45° scanning angles covering the frequency range from 8 to 26.5 GHz (X, Ku, and K-bands) by taking the antenna element spacing as half the wavelength at each calculated frequency.

In this paper, a continuously variable optical time delay module, based on a thermally tuned optical fiber, is presented and demonstrated. This type of fiber true time delay module can be implemented into an optically fed phased array antenna system similar to that described by Shi et al. [11]. To the authors' knowledge, this work is the first time that a thermally tuned bare optical fiber is demonstrated to generate time delay values for a phased array antenna. Discussed herein is the physical operating principle of the thermally tuned fiber delay lines as well as experimental results for single-mode silica fiber and multimode polymer optical fiber.

2. Principle

The normalized propagation constant for single-mode optical fiber, β, can be approximated by [12]

$$\beta = \frac{n_{\text{eff}} - n_2}{n_1 - n_2} \approx (1.1428 - 0.996/V)^2, \quad (1)$$

where n_{eff} is the effective index of the guided mode and

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

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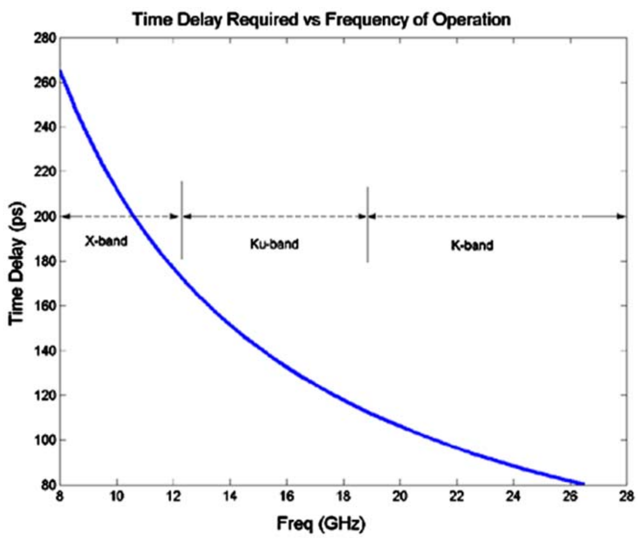

Fig. 1. The time delay requirements for a 4 × 4 subarray of a PAA with ±45° steering angle across X, Ku, and K frequency bands.

and a is the core radius, n_1 and n_2 are the refractive indices of the core and cladding, respectively, and λ is the free space propagating wavelength. Empirically, this approximation is accurate to within 0.2% for a V parameter in the range of 1.5–2.5. From Eq. (1), the change in the effective index for a given change in temperature can be derived to be

$$\frac{dn_{eff}}{dT} = \frac{dn_1}{dT}(A+B) + \frac{dn_2}{dT}(C-A), \quad (2)$$

where

$$A = \left(1.1428 - \frac{0.996\lambda}{2\pi a\sqrt{n_1^2 - n_2^2}}\right)^2,$$

$$B = \frac{\sqrt{A}n_1(n_1-n_2)0.996\lambda}{\pi a(n_1^2-n_2^2)^{3/2}},$$

$$C = 1 - \left(\frac{\sqrt{A}n_2(n_1-n_2)0.996\lambda}{\pi a(n_1^2-n_2^2)^{3/2}}\right).$$

The overall time delay produced, $\Delta\tau$, will be

$$\Delta\tau = \frac{dn_{eff}}{dT}\frac{\Delta T\, l}{c}, \quad (3)$$

where ΔT is the change in temperature of the fiber, l is the length of the fiber, and c is the speed of light in vacuum.

For standard telecommunication single-mode fibers, the $A+B$ constant is approximately three times the value of the $C-A$ term. This gives a larger weighting to the dn/dT factor of the core material. From this solution, it is seen that in order to maximize the dn_{eff}/dT value and hence $\Delta\tau$, the magnitude of dn/dT for both the cladding and core should be as large as possible.

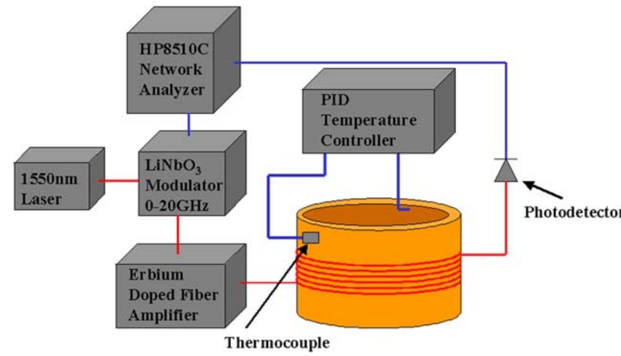

Fig. 2. Schematic of the setup used to control the temperature of the thermally tuned fiber delay line and measurement of the respective time delay.

3. Experiment and results

A test structure was developed in order to demonstrate the time delay properties of thermally tuned fiber. Fig. 2 shows a schematic of the closed-loop system used to measure the time delay as a function of temperature.

A copper pipe, three inches in diameter by 2 in. in height, was lined with a heating blanket that was connected to a proportional integral derivative (PID) temperature controller. A thermocouple was externally attached to the copper pipe with thermally conductive epoxy. The thermocouple was connected to the PID controller to form a feedback loop. The section of the fiber to be tested was wrapped around the outside of the copper pipe. Because the thermocouple and fiber are both in intimate contact with the outer surface of the copper pipe, any temperature gradient from the heater, through the thickness of the copper pipe, is irrelevant. Temperature gradients along the length of the pipe are also negligible due to the high uniformity of heating from the heating blanket.

An HP 8510C network analyzer was used to generate sinusoidal waveforms of frequencies ranging from 2 to 14 GHz. The output electrical signal from the network analyzer was fed into a lithium niobate electro-optic modulator. A CW laser operating at 1550 nm was also fed into the optical modulator. The modulated output was amplified by an erbium doped fiber amplifier (EDFA) and then connected to the input end of the thermally tuned fiber that was wrapped around the copper heater. The output of this fiber was connected to a PIN photodetector with a bandwidth of 0–18 GHz. The electrical signal from the photodetector was fed back into the network analyzer in order to measure the phase. The phase angle of the received signal was measured at 2 GHz increments between 2 and 14 GHz at temperature intervals starting at 30°C and increasing in 10° increments to the maximum operating temperature of the fiber. The 2–14 GHz measurement range was chosen in order to collect data points over a wide range of frequencies in order to enable accurate curve fitting. Larger measurement frequencies were not possible due to bandwidth limitations of

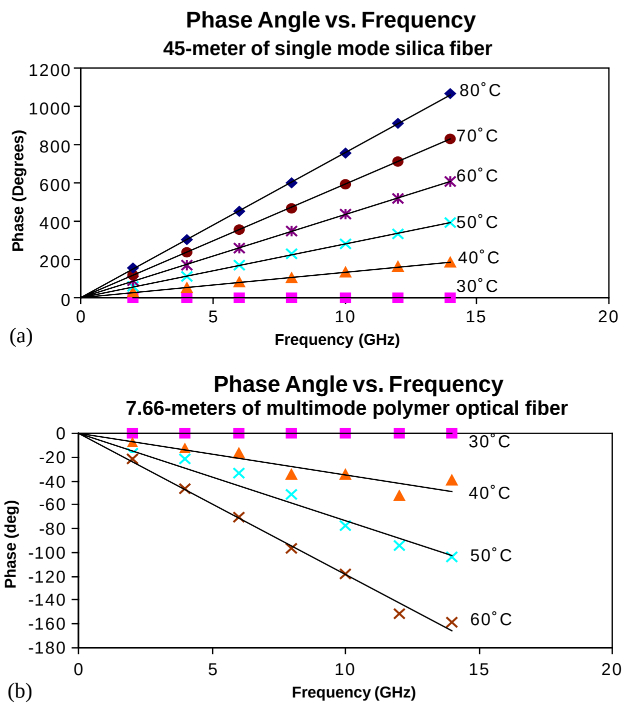

Fig. 3. Measurement results showing the phase angle as a function of frequency for (a) 45-m section of Corning LEAF silica fiber, (b) 7.66-m section of Lucina polymer optical fiber. Larger slopes, as the temperature increases, represent greater amounts of time delay.

the equipment. The temperature control loop was capable of maintaining the set point temperature to within ±1°C.

Lucina polymer fiber was chosen for comparison with glass LEAF fiber from Corning. The propagation loss of Lucina fiber is 250 dB/km at the communication wavelength of 1.55 μm while the propagation loss of LEAF fiber is 0.05 dB/km.

Fig. 3a shows plots of the phase angle with respect to the frequency for a Corning LEAF single-mode glass fiber at temperatures of 30°C, 40°C, 50°C, 60°C, 70°C, and 80°C. The slope of each line is used to calculate the time delay for that temperature. The time delay values are measured with reference to the fiber having zero delay at 30°C. Fig. 3b shows similar data for a 7.66-m section of Lucina multimode polymer optical fiber at temperatures of 30°C, 40°C, 50°C, and 60°C. Lucina fiber has a maximum operating temperature of 65°C so it could not be tested at higher temperatures.

The delays per unit length are plotted against the temperature in Fig. 4, where a linear relationship between the time delay and the temperature is experimentally confirmed for both types of fiber. A thermal time delay factor representing the amount of time delay for a given temperature change per unit length of fiber can be assigned from the slope of the fitted lines in Fig. 4. For silica LEAF fiber and polymer Lucina fiber the thermal time delay factors are 0.096 and −0.1427 ps/m°C, respectively. The negative time delay factor of the polymer fiber is due to the negative dn/dT value of the polymer material.

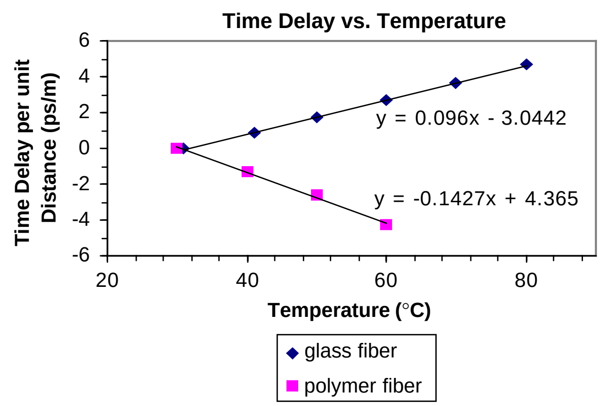

Fig. 4. Time delay per unit length of fiber plotted against temperature for silica and polymer fibers. The silica fiber was 45 m long and the polymer fiber was 7.66 m. The plots are linear showing the time delay is directly proportional to the temperature of the fiber.

The total amount of time delay produced with a 45-m single-mode silica fiber is 211 ps over a 50°C tuning range. The insertion loss, 0.2 dB, of this thermally tuned LEAF fiber was measured as a function of temperature and was found to be constant across the entire tuning range. The total amount of time delay produced with the 7.66-m multimode fiber is 32 ps over a 30°C tuning range. The delay provided by the silica fiber is adequate to cover the Ku and K-band requirements of the 4 × 4 subarray shown in Fig. 1.

Because polymer materials typically have a $|dn/dT|$ value an order of magnitude greater than that of glass, it was theorized that thermally tuned optical fiber with polymer core and cladding could introduce time delays at least ten times greater than those of glass fiber. The results show that the polymer fiber did not perform as well as was expected. The ratio of thermal time delay factors shows that the polymer fiber only provides 67% more time delay than glass fiber for a given temperature change and length. This may be explained by the coefficient of thermal expansion (CTE) for the two fiber types. The CTE of the perfluorinated polymer used in Lucina fiber is approximately $75 \times 10^{-6}\ K^{-1}$, while the CTE for the SiO_2 used in the Corning glass optical fiber is approximately $0.5 \times 10^{-6}\ K^{-1}$. The large thermal expansion of the polymer fiber may partially negate the time delay provided by the decrease in effective index as the temperature is increased. However, for the glass fiber, the thermal expansion may actually add to the time delay achieved from the positive effective index change.

4. Conclusion

By using an approximation of the single-mode fiber propagation constant, an analytical expression for the change in effective index for a given change in temperature has been derived. It has been shown that in order to obtain a large change in the effective index of a waveguide, the dn/dT values of both the core and cladding material should be large.

This response of the effective index for a change in temperature is used to produce a continuously tunable time delay line with optical fiber. A 45-m single-mode Corning LEAF fiber is demonstrated to produce up to 211 ps of delay over a temperature tuning range of 50°C. A thermal time delay factor is introduced and the factor's value for Corning LEAF fiber is 0.096 ps/m°C. A 7.66-m multimode Lucina polymer fiber produces up to 32 ps of delay over a 30°C tuning range. The thermal time delay factor for this type of fiber is −0.1427 ps/m°C.

This novel time delay generation technique can provide large delay values with minimum insertion loss when compared with other photonic delay methods [1–10]. By simply extending the length of heated fiber, even larger amounts of delay can be achieved without a significant loss penalty. This time delay method should prove to be very useful for large scale PAA systems that require large optical delays.

Acknowledgements

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