A Six Bit Silicon Nitride Optical True Time Delay Line for Ka-Band Phased Array Antenna

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Abstract. A six-bit optical true time delay unit with a delay tuning increment of 1.42 ps was designed and fabricated on silicon nitride platform, which can be utilized in Ka-band phased array antenna systems. The delay unit consists of seven thermo-optical switches and six waveguide delay lines with different lengths. By changing the states of the thermo-optical switches, 64 stages of discrete time delays varying from 0 to 89.6 ps has been obtained. In addition, as the waveguide delay independence on the modulation frequency, so the designed silicon nitride delay unit can be applied in microwave applications with broader bandwidth.

1. Introduction
With the rapid development of interactive multimedia technology (such as high-definition video, video phone, etc.), users put forward higher requirements for communication bandwidth [1]. However, the current wireless network bandwidth will not be able to meet the growing demand for communication bandwidth. A solution to improve the bandwidth of future wireless networks is to use phased array antenna (PAA) with high directivity to replace the former omnidirectional antenna, as shown in Figure 1 [2]-[4]. By rapidly switching the beam direction of phased array antenna, the signal can be transmitted to different users in time-sharing [5]-[7]. Therefore, as long as the switching rate of this beam direction is fast enough, the switching waiting time can be ignored.

![Fig. 1. Beam scanning diagram of phased array antenna.](image)

The phased array antenna is composed of several closely adjacent antenna units (which can be dipole antenna, microstrip antenna, aperture antenna, horn antenna, etc.), as shown in Fig. 2, it is a PAA with arrangement period of d composed of four antenna units.
Fig. 2. Schematic diagram of four element PAA array.

The spacing \(d\) determines the width of the beam, and the size of the antenna unit spacing \(d\) is usually the order of the transmitted microwave signal wavelength. And the phase delay \(\Delta \psi\) of the signal on the adjacent antenna unit controls the scanning angle \(\theta\) of the transmitted beam. The microwave signal emitted by each PAA unit can be regarded as an independent plane wave in the far field. If the microwave signal emitted by each PAA unit causes the far-field plane wave front to interfere with each other in the target direction \(\theta\), then the beam emission along the direction of \(\theta\) can be realized. At this time, the path difference \(d \times \sin \theta\) corresponding to the phase difference \(\Delta \psi\) of the microwave signal in the air is

\[
\Delta \phi = \frac{2 \pi \cdot d \cdot f}{c} \cdot \sin \theta
\]

(1)

It can be seen from this expression that if the phase shifter scheme is used, the phase shift \(\Delta \psi\) is related to the frequency \(f\) of the RF signal. If the RF signal frequency \(f\) changes, but the phase shift \(\Delta \psi\) does not change, it will cause beam deflection. Therefore, the signal frequency change will cause the beam to deviate from the target direction ("squint effect"), that is, broadband phased array antenna cannot be realized. The beam deviation angle caused by the change of RF frequency can be expressed as follows:

\[
\Delta \theta = \frac{\Delta f}{f} \cdot \tan \theta
\]

(2)

Where \(\Delta \theta\) is the offset of scanning direction, \(f\) is the signal frequency, \(\Delta f\) is the variation of signal frequency, and \(\theta\) is the beam target angle.

Where \(d\) is the distance between adjacent antenna units, \(f\) is the frequency of microwave signal transmitted, \(\theta\) is the beam scanning angle, and \(c\) is the speed of light in free space. In general, the phase difference \(\Delta \psi\) between signals of adjacent antenna units can be realized by the time delay \(\Delta \tau\) of signals.

\[
\Delta \tau = \frac{d}{c} \cdot \sin \theta
\]

(3)

It can be seen from equation (3) that when the phase-shifting scheme is replaced by the delay scheme, the delay required to realize beam deflection is independent of the RF signal frequency. Therefore, the "squint effect" caused by the phase-shifting scheme can be overcome and the broadband beam scanning of PAA antenna can be realized.

2. Silicon Nitride Delay Line Design and Fabrication

The structure of a typical optical beam forming system is shown in Fig. 3. By modulating the radio frequency signal to the optical frequency, forming the beam shaping unit by the optical amplitude control unit, and forming the beam deflection unit by the optical delay unit, the optical beam forming system can achieve lower signal transmission loss, higher working bandwidth, anti-electromagnetic interference and so on. Signal splitting can be realized by two schemes: 1. Single wavelength laser + modulator + beam splitter; 2. Multi wavelength laser + modulator + WDM. For the first scheme, the laser emitted by
the single wavelength laser enters the electro-optic modulator, and the radio frequency signal to be transmitted is modulated to the laser carrier through the modulator. After the modulated optical signal is shaped by the optical amplitude controller (optical attenuator), the beam deflection is realized by adjusting the delay time by the optical delay unit, and finally enters the photoelectric system The detector array obtains the RF signal and drives the phased array antenna.

Fig. 3. Transmitting unit of phased array antenna based on optical beamforming.

The silicon nitride optical switch delay line is designed based on the silicon nitride double strip waveguide, and the waveguide section is shown in Fig. 4 (c). The width of the core is $w = 1.1 \mu m$, the height of the two core layers are $t_1=175$ nm, $t_2=75$ nm, respectively. The distance between the two cores is $t_{in} = 100$ nm, and the waveguide dip angle $\alpha = 82^\circ$. Both the upper and lower cladding layers of the waveguide are silicon dioxide with a thickness of 8 $\mu m$. The 6-bit delay line is composed of seven cascaded thermo-optical switches and six waveguide delay lines with different lengths. Its structure is shown in Fig. 4(a). The structure diagram of the thermo-optical switch is shown in Fig. 4(b). The thermo-optical switch adopts Mach Zehnder interference structure, which is composed of two input / output 3 dB directional couplers and two upper and lower interference arms with a length of 1000 $\mu m$. There is a heating electrode in the upper arm, which is mainly made of gold, with a length of 1000 $\mu m$ and a width of 20 $\mu m$. The upper arm of the switch is heated by the electrode. Because the silicon nitride material has thermos-optical coefficient, the change of temperature can change the thermos-optical coefficient of silicon nitride material, thus changing the refractive index of the material. When the refractive index of the upper arm of the thermos-optical switch changes, the phase difference between the two arms will change. When the phase difference satisfies the interference cancellation condition, the output optical power is the minimum, which is called the off state of the switch. When the phase difference satisfies the condition of constructive interference, the output optical power is the maximum, which is called the on state of the switch. By tuning the states of the thermos-optical switch, the delay path of the light can be changed to achieve different delay states. The 6-bit delay line unit can realize 64 delay states from $0 \Delta\tau$ to $63 \Delta\tau$.

Fig.4. (a) The architecture of a 6-bit delay unit with test ports. (b) The structure of the thermo-optical switch. (c) The cross-section of the double strip silicon nitride waveguide.

The group index of the double strip silicon nitride waveguide is about 1.77. Hence, the waveguide lengths of the six waveguides delay lines are calculated and listed in Table 1.

| $\Delta L$ | $\Delta\tau$ | $2\Delta\tau$ | $4\Delta\tau$ | $8\Delta\tau$ | $16\Delta\tau$ | $32\Delta\tau$ |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|
| 240.678$\mu m$ | 481.356$\mu m$ | 962.712$\mu m$ | 1925.424$\mu m$ | 3850.847$\mu m$ | 7701.695$\mu m$ |
3. Measurement Results
Firstly, the response and transient response of the optical switch under different driving current were tested. The "Cross" state is defined as optical signal injected into "in0" port (or "in1" port), and then switched to "out1" port (or "out0" port). The "through" state indicates that the optical signal is transmitted from the "in0" port (or "in1" port) to the "out0" port (or "out1" port). As shown in Fig. 5 (a), the optical switch has an extinction ratio greater than 25 dB, which is mainly limited by the output imbalance of the directional coupler. According to experimental results, the transmittance is normalized to 0 dB, and the insertion loss of a single optical switch is about 3 dB. The volt ampere characteristic curve of the optical switch is shown in Fig. 5 (c), and the resistance value of 260 Ω can be obtained. Therefore, the "off" state current and "on" state current of the black curve are about 9.03 V and 13.01 V respectively. Then the transient response test was carried out to measure the response time of the optical switch. A square signal with a frequency of 100 Hz was applied to the switch electrode. The low voltage and high voltage were set to 9.03 V and 13.01 V respectively. The rise time and fall time of the switch are 95.279 μs and 138.56 μs, respectively.

Then, the "cross" and "through" states of seven optical switches were measured before measuring the 64 stages of delay time. The optical signal was injected into the in0 port of the tested switch and the transmittance’s dependence on the applied current was monitored at the following test port, and a curve that is similar to the curves in Fig. 5(a) was obtained. The current of the first minimal transmittance is regarded as the "through" state current of the switch. Then, the current of the adjacent maximal transmittance at the right side of the "through" current is regarded as the “cross” state current of the switch. In this case, the “through” and “cross” state currents of the seven optical switches can be easily and accurately find out. The applied currents needed to maintain the “through” states and the “cross” states (denoted as I<sub>t</sub> and I<sub>c</sub>) of each state are shown in following Table 2.

| Switch NO. | Switch1 | Switch2 | Switch3 | Switch4 | Switch5 | Switch6 | Switch7 |
|------------|---------|---------|---------|---------|---------|---------|---------|
| I<sub>t</sub> (mA) | 25.14 | 30.42 | 30.9 | 41.7 | 28.2 | 25.32 | 29.76 |
| I<sub>c</sub> (mA) | 44.28 | 47.34 | 47.16 | 55.2 | 45.3 | 43.54 | 45.9 |

Fig. 5. The switch’s transmittances versus the applied current tested under “cross” state and “through” state. (b) The transient response of the switch compared with the driving voltage. (c) Volt ampere characteristic curve of optical switch.

The link used to test the delay is shown in Fig. 6. The output optical power of the laser (santac WSL-100) is 15 dBm. The RF signal from Aglient (n5242a) is modulated to the optical carrier through the modulator (push-pull-20 GHz). The modulator works at the orthogonal offset point, and the modulated optical carrier will produce two optical sidebands with the same amplitude. The light passing through the delay line unit changes the optical signal into electrical signal through the photodetector (Finisar xpdv2120ra), and the vector network instrument receives the electrical signal and measures the time delay.
Fig. 6. The experimental setup of the microwave photonics link utilized to measure the delay line. LD: laser diode, PC: polarization controller, PD: photodetector, LNA: low noise amplifier, VNA: vector network analyzer.

Fig. 7 shows the measured 64 delay times (from 0Δτ to 63Δτ) compared with the designed values. The measured delay times versus the number of delay stages shows good linearity with a slope about 1.4 ps/stage, which is a bit smaller than the designed 1.42 ps/stage. That may result from the fabrication error of the double strip silicon nitride waveguide that leads to the group index deviation between the fabricated chip and the design.

Fig. 7. The measured 64 delay times (from 0Δτ to 63Δτ).

4. Conclusion
A six-bit delay unit designed for a 40 GHz PAA has been presented. The delay unit is produced on a silicon nitride chip with a compact size of 32mm by 32mm. 64 stages discrete delay times varying from 0 ps to 89.6 ps have been obtained. The waveguide delay line has the natural advantage of being wavelength-insensitive. Therefore, the proposed OTTD unit has a large bandwidth, allowing it to be applied in some broadband microwave applications.

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