DOUBLE-LOADED EO MAGNETIC FIELD PROBE WORKING ABOVE 10 GHz

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Abstract: This paper describes an optical magnetic field probe consisting of a loop antenna element doubly loaded with LiNbO$_3$ electro-optic crystals. The probe can work above 10 GHz for magnetic field detection near a microstrip line. Using optical technology, it realizes electrical hybrid operation of a conventional double-loaded loop probe and requires no metallic cables or electrical hybrid junction. We examined probe characteristics for magnetic field detection up to 20 GHz. We confirmed that the probe can work above 10 GHz for magnetic near-field detection with suppression of electric field influence.

Key words: Probe, Loop antenna, Electro-optic crystal, Electromagnetic near-field, Pockels effect

1. Introduction

Loop antenna probes are fundamental tools for magnetic field detection [1]. However, the probes encounter difficulties caused by metallic loop elements. The elements pick up electric fields, which induce undesired signals in magnetic field detection. Double-loaded loop probes have been developed to suppress this influence electrically [2], [3]. Although an electrical hybrid junction of the probe suppresses that influence, its operation is frequency-dependent. Also, metallic cables pick up electric fields and disturb the surrounding field that is to be measured.

We have studied a new type of optical probe to detect electromagnetic near-fields with high accuracy up to the gigahertz range. We have reported on characteristics of a double-loaded EO magnetic field probe [4]. Its probe head comprises a loop antenna element and two LiNbO$_3$ electro-optic crystals. Using optical technology, it realizes electrical hybrid operation of a conventional double-loaded loop probe and requires no metallic cables or electrical hybrid junction (optical hybrid operation). The probe allows measurement of electromagnetic fields with little invasive impact with respect to the surroundings [5]. Furthermore, the detected signal can be transmitted without any disturbance caused by the noise picked up by metallic cables. These characteristics imply that the probe is suitable for highly accurate near-field measurements.

This paper describes a new double-loaded EO magnetic field probe. We examined probe characteristics for magnetic field detection up to 20 GHz. The probe, smaller than former probes, has resonant frequency above 10 GHz and its optical hybrid operation provides highly accurate magnetic field measurement with suppression of electric field influence.

2. Double-Loaded EO Magnetic Field Probe

2.1 Probe Head and System Configuration

Fig. 1 shows the probe head of the double-loaded EO magnetic field probe. It comprises a patterned loop element and two LiNbO$_3$ electro-optic crystals. LiNbO$_3$ is a ferroelectric uniaxial crystal that polarizes along the c-axis (optical axis) of its crystal lattice. Importantly, c-axes of the LiNbO$_3$ in the probe head directly oppose each other. Fig. 2 shows their dimensions.

The probe head, with no metallic cables or balun, provides a means to measure magnetic fields with little invasive impact with respect to the surrounding field that is to be measured. Furthermore, the detected signal can be transmitted without any disturbance caused by the noise picked up by metallic cables.

![Fig. 1 Probe head](image-url)
2.2 Optical Hybrid Operation

The optical hybrid operation consists of optical separation of magnetic field signals from electric field signals [4]. The case we consider is that a magnetic field $H$ penetrates perpendicularly to the loop element and that a uniform electric field $E$ is present on the loop plane (Fig. 4). A voltage induced by $E_y$ is cancelled at the LiNbO$_3$ because of structural symmetry of the probe. Thereby, $E_z$ induces $V_E$.

Voltages $V_H$ induced by $H$ modulate the beam twice because $V_H$ directs $+c$ at both LiNbO$_3$. On the other hand, voltage $V_E$ induced by $E$ at one of the two LiNbO$_3$ directs $+c$ whereas $V_E$ at the other LiNbO$_3$ directs $-c$. Thereby, the optical modulation is cancelled after the beam passes the two LiNbO$_3$. That is, only $H$ gives modulation to the beam passing through the probe head.

Through the process explained above, the probe head realizes electrical hybrid operation of a conventional double-loaded loop probe using optical technology. It requires no metallic cables or electrical hybrid junction. After the beam leaves the probe head, it is modulated to an appropriate intensity by conventional optical intensity modulation.

2.3 Examination with an Equivalent Circuit

We examined the probe outputs with an equivalent circuit. Under an electrically small loop condition, a simple equivalent circuit of a square loop antenna is represented by the self-inductance $L$ of the loop and a voltage source based on Faraday’s law of electromagnetic induction (Fig. 5). Two $C_{LN}$ represent capacitances of the loads with the LiNbO$_3$.

Fig. 6 shows the calculated outputs [4]. The LC resonant frequencies for each probe are 7.2 and 13.9 GHz, respectively.

![Fig. 2 Dimensions of probe-A and B](image)

![Fig. 3 Probe system](image)

![Fig. 4 Induced voltages and the arrangements of $+c$ directions](image)

![Fig. 5 Equivalem circuit](image)

![Fig. 6 Calculated outputs](image)
3. Experimental results

3.1 Experimental Conditions

Fig. 7 shows the experimental setting for the probe. A microstrip line (MSL) was used as an electromagnetic field source. The MSL had a 1.0-mm-wide line with a 100 × 245 mm periphery and was matched to 50 Ω.

The loop element was set either parallel or orthogonal to the line. Under the parallel setting (H_{\text{max}}), the loop element received the maximum amount of magnetic flux. Under the orthogonal setting (H_{\text{min}}), the loop element received no magnetic flux. Distance between the MSL and the bottom of the loop element was maintained at 0.5 mm.

Resolution bandwidth of the spectrum analyzer was set to 100 Hz throughout the experiments. The noise floor of our probe system was −120 dBm, as determined by the spectrum analyzer.

![Fig. 7 Experimental setting] 245 mm
100 mm
1.0 mm
Scan
0.5 mm
50 Ω
Termination

3.2 Frequency Response

We examined the probe frequency responses. The MSL was powered at 10 dBm over the frequency range from 0.1 to 20 GHz. The 14 mA electric current flows along the line. The probe heads were set above the center of the line under the H_{\text{max}} setting.

Fig. 8 shows experimental results. The plots show the responses to the magnetic field. Resonant frequencies for each probe are 5.8 and 14 GHz, respectively.

![Fig. 8 Frequency response]

3.3 Linearity

We next examined the linear response of the Probe-B. The input power to the MSL ranges from −20 to +18 dBm. The probe head was set above the center of the line under the H_{\text{max}} setting.

Fig. 9 shows experimental results. Linear responses under the condition were observed. The different outputs at every frequency reflect the frequency characteristic shown in Fig. 8.

![Fig. 9 Linearity of Probe-B]

3.4 Electromagnetic Field Distribution above the MSL

We measured magnetic field distribution above the MSL powered at 10 dBm at 3 GHz. We scanned the probe heads horizontally at a right angle to the line under the settings of H_{\text{max}} and H_{\text{min}}.

Figs. 10–12 show experimental results. The horizontal axis shows the probe head position from the line and the vertical axis shows outputs normalized by the maximum output. Fig. 10 shows the result for a single-loaded EO magnetic field probe with the same loop dimensions as Probe-A [6]. The probe has no optical hybrid operation because it uses an only LiNbO₃. Figs. 11 and 12 show results with Probe-A and B, respectively.

The H_{\text{max}} results demonstrate that all the optical probes can measure a magnetic field distribution near the MSL. On the other hand, H_{\text{min}} outputs are not desired for magnetic field probes because no magnetic flux penetrates the loop aperture. Therefore, the ratio of H_{\text{max}} to H_{\text{min}} (H_{\text{max}}/H_{\text{min}}) can be regarded as a D/U ratio. The result indicates that the optical hybrid operation can suppress electric-field influence (H_{\text{min}} outputs) effectively. Furthermore, the Probe-B (Fig. 12) improves H_{\text{max}}/H_{\text{min}} compared to Probe-A (Fig. 11).

We also measured distribution near the MSL at 10 GHz with Probe-B. Fig. 13 shows the result.

4. Conclusion

We have demonstrated that the new double-loaded EO magnetic field probe can work above 10 GHz for magnetic near-field detection with suppression of
electric field influence. The probe shows linear responses to power input to the MSL from –20 to +18 dBm in the gigahertz range. We also observed that optical hybrid operation can suppress electric-field influence effectively in magnetic near-field measurements. Those imply that the probe is suitable for highly accurate magnetic near-field measurements in the gigahertz range.

Fig. 10 Near-field measurements at 3 GHz with a single-loaded EO magnetic field probe

Fig. 11 Near-field measurements at 3 GHz with Probe-A

Fig. 12 Near-field measurements at 3 GHz with Probe-B

Fig. 13 Near-field measurements at 10 GHz with Probe-B

References