A broadband directional coupler based on ferrite cores

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A broadband directional coupler based on ferrite cores is proposed for high frequency (HF)/Very high frequency (VHF)/Ultra High Frequency (UHF) communication systems. The transformer-type coupler is composed of two double-aperture ferrite cores and 1-mm-diameter strands. The ferrite cores with different relative permeabilities are screened to achieve an ultra-wide bandwidth (5 – 1000 MHz). The coupler demonstrates excellent electric performances. The voltage standing wave ratio of each port is less than 1.2, a stable −20 dB coupling level is maintained over the operating bandwidth and the insertion loss is less than 0.8 dB. Such couplers have compact sizes and are of very low cost.

Introduction: The directional coupler is one of the most important components in transceiver system, which can realise power division or/and power combination. Conventional couplers are generally fabricated with coupling micro-strip lines or metal waveguides [1–3]. However, these techniques are problematic in HF/VHF/UHF applications. The physical size and high cost make it impossible to be applied in highly compact and wideband systems. Lump components can also be used to fabricate couplers, but the insertion loss is too high [4]. The ferrite-core transformer is an element that is commonly used in megahertz circuits because of its important functions such as wideband and impedance transformation. In 2013, Madishetti et al. developed the complete analytical model for dual or six-port directional coupler using ideal radio frequency (RF) transformers [5]. Then, Wu et al. proposed an analytical design method of a transformer-based quadrature directional coupler, which utilised multi-section topology and complex circuits to broaden the operation bandwidth [6]. Two years later, this group further presented a class of quadrature couplers based on ferrite-core transformers and reactive lumped elements, which could provide backward-wave coupling at 13.56 MHz band [7]. This letter presents a miniature broadband directional coupler based on ferrite-core transformers. This device can realise the coupling factor of −20 dB from 5 to 1000 MHz while keeping the voltage standing wave ratio (VSWR) of each port less than 1.2. The maximum insertion loss at high frequencies is less than 0.8 dB.

Circuit design and analysis: The transformer-type coupler mainly has two implementation methods: the series coupling and shunt coupling [8], as shown in Figure 1. For the series coupling structure, the phase of the coupling signal depends on the transmission direction of the input signal, while for the shunt coupling structure, the phase of the coupling signal is always consistent with the input signal. If a hybrid structure of the series coupling and shunt coupling is applied, we can realise a bidirectional coupler. Figure 2 shows the circuit diagram of a bidirectional coupler, where TR1 is series connected and TR2 is shunt connected. The power coupled by the two transformers is guided into input ports of a magic-T network, $\text{T}_{\text{ps}}$, which can realise the equal amplitude and in-phase synthesis of the two signals at the coupling end, and equal amplitude and anti-phase cancellation at the isolation end. However, such a circuit requires a specially designed magic-T and reasonable turn ratios of the two transformers to ensure equal amplitudes of the two coupled signals.

In our design, the directional coupler is composed of two tightly coupled transformers with the turn ratios to be $N_1:1$ and $N_2:1$, respectively. The schematic diagram of the coupler is shown in Figure 3. In general, if the ferrite cores are assumed to be lossless, then the voltage and current through turn ratios of the directional coupler at each port can be approximated as

\[
V_2 = N_2 (V_1 - V_3)
\]
\[
V_4 = N_1 (V_2 - V_3)
\]
\[
I_1 = N_1 (I_1 + I_2)
\]
\[
I_3 = N_3 (I_1 + I_2)
\]

The scattering parameters can be further obtained by utilising the incident and reflected waves, which are designated in terms of $a_i$ and $b_i$:
where $S_2$ is the element of the scattering matrix. By relating the incident and reflected waves, we can easily obtain

$$
\begin{align}
S_{11} &= -S_{44} = \frac{1}{2} (-N_1^2 + N_2^2 - 2N_1N_2 + 1) \\
S_{22} &= S_{33} = \frac{1}{2} (-N_1^2 + N_2^2 + 2N_1N_2 - 1) \\
S_{12} &= S_{43} = \frac{2N_1N_2}{2} (2N_1N_2 - 1) \\
S_{13} &= S_{24} = -\frac{2N_1N_2}{2} (N_1 + N_2) \\
S_{14} &= -\frac{2N_1N_2}{2} (N_1N_2 + N_2^2 + 1) \\
S_{25} &= \frac{2N_1N_2}{2} (N_1N_2 - 1 - N_2^2)
\end{align}
$$

where

$$d = 4N_1^2N_2^2 + 1 + (N_1 - N_2)^2. \tag{4}$$

Figure 4(a) shows the photograph of the fabricated directional coupler, where the isolated port is connected with a 50 Ω resistor. Figure 4(b) shows the equivalent circuit diagram. Both transformers, TR1 and TR2, are composed of double-aperture ferrite cores and two 1-mm-diameter single strands. The ends of TR1 and TR2 are connected together to a 50 Ω resistor. The turn ratios of TR1 and TR2 are $N_1 = 9$ and $N_2 = 7$, respectively. In our design, ferrite cores with different relative permeabilities are measured. Figure 5(a) shows the measured coupling coefficients of the coupler. From the figure we can see that for ferrite cores with $\mu_r \lesssim 2000$, the coupling coefficient drops quickly with the increase in frequency. While for the ferrite core with $\mu_r = 2500$, the coupling level seems to remain constant (-20 dB) from 5 to 1000 MHz. For $\mu_r \gtrsim 4300$, the electrical performance deteriorates again. Therefore, the ferrite (Mn–Zn) core with $\mu_r = 2500$ is adopted. Figure 5(b) shows the measured VSWRs of the three ports. With the increase in the operating frequency, the insertion loss, as expected, rises slightly from 0.4 dB (at 5 MHz) to 0.8 dB (at 1000 MHz), which should be due to the increase in the stray capacitance between windings. Figure 5(c) further shows the measured VSWRs of the three ports, which are less than 1.2 in the whole band. Table I shows the comparison between the proposed coupler and other recent works. This design has the main advantages of wider bandwidth and smaller volume.

**Conclusion:** This work presents a broadband, miniature and low-loss directional coupler based on double-aperture ferrite cores. The proposed coupler exhibits excellent performances in a wide band (5–1000 MHz), such as low insertion loss (<0.8 dB), constant coupling level (~20 dB) and low return loss (VSWR < 1.2). Such design is especially applicable for highly compact and wideband HF/VHF/UHF circuits.

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**Table 1. Comparison between this design and other recent works**

| Ref. | Working frequency | Coupling coefficient | Structure |
|------|-------------------|----------------------|-----------|
| [7]  | 12–15 MHz         | −3 dB                | Transformers |
| [9]  | 10–18.9 GHz       | −31 dB               | Wave guide |
| [10] | 2.5–3.5 GHz       | −4, −6, −8, −10 dB   | Micro-strip circuit |
| [11] | 5–150 MHz         | −45 ± 1.3 dB         | coaxial cable |

This work 5–1000 MHz −20 dB Transformers
Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflict of interest: The authors declare that there is no conflict of interest.

Contribution statement: L. Liu and N. Song: Investigation and writing; Z. B. Wang: Supervision, review & editing.

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