Stable multiple non-Foster circuits loaded waveguide for broadband non-dispersive fast-wave propagation

J. Long and D.F. Sievenpiper

Periodically loading non-Foster circuits (NFCs) in a conventional waveguide has been proved to be possible for achieving broadband non-dispersive fast-wave (FW) propagation. However, the unconditional stability of such structures has been argued due to the multiple NFC loadings. Despite the potential instability, it is demonstrated that the NFC-loaded waveguide can still be stable for specific terminations, in particular, with the 50 Ω load that is commonly used in radio frequency/microwave applications. For purpose of demonstration, a NFC-loaded waveguide that contains substantially more unit cells than in prior work has been designed and measured, showing a stable and causal FW propagation with a 1.2 c phase velocity over the bandwidth of 80–120 MHz.

Introduction: Many researchers have demonstrated that waveguides with periodically loaded non-Foster circuits (NFCs) have the capability of broadband non-dispersive fast-wave (FW) propagation [1, 2], which has been proposed for broadband leaky-wave antennas [3, 4], series antenna feeding structures [5], broadband electromagnetic cloaking metasurfaces [6] and so on. However, to the best of the present authors' knowledge, only a few researchers have successfully realised and measured broadband FW propagation, and only three cascaded NFC-loaded unit cells at most have been reported [1, 2]. Moreover, waveguides with NFC loads have further been challenged by the lack of unconditional stability [7], which puts doubts on their practical application in antennas and metasurfaces. In fact, based on the Foster theorem, any passive element must have Foster reactance [8], so NFCs always present gain along with the non-Foster reactance, and thus cascading more NFC-loaded unit cells results in potential instability. Nevertheless, despite the potential instability, multiple NFC-loaded waveguides can still be stable with specific loads, such as 50 Ω, which is usually used as a termination in radio frequency/microwave circuits.

In this Letter, we report the design and fabrication a 10-unit-cell NFC-loaded waveguide, which contains significantly more unit cells than the prior work. To guarantee the stability, smaller negative capacitance is utilised so as to achieve less negative resistance. The fabricated waveguide was tested with various methods for verifying the stability, including transient measurement, spectrum analysis and Kramers-Kronig (K-K) relations. The retrieved phase velocity is 1.2 c over a bandwidth of 80–120 MHz. The experimental verification shows that even though the waveguide is potentially unstable, it can still be stable with specific loads, which further demonstrates the possibility of implementing electrically long leaky-wave antennas and metasurfaces.

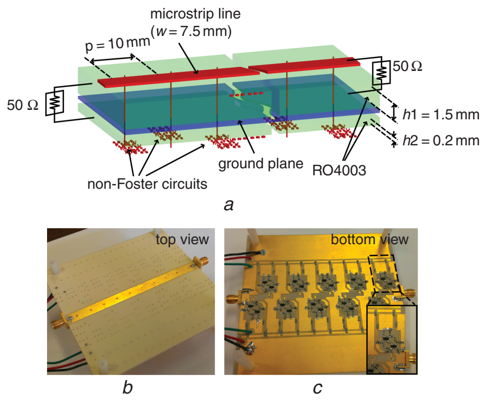

Fig. 1 *NFC-loaded FW waveguide*

a Illustration of designed waveguide incorporated with active circuits
b Top view of fabricated waveguide
c Bottom view

Design of periodically non-Foster-loaded waveguide: Fig. 1 illustrates the NFC-loaded waveguide. It consists of three layers. The top layer is the microstrip line (MLine), which periodically connects to the NFCs (bottom layer) through vias. The bottom layer is for the NFCs, where 10 NFC layouts are printed in alternative direction to the MLine. The middle layer is the common ground plane for both the MLine (top layer) and the NFCs (bottom layer), which also provides isolation between both the top and bottom layers. RO4003 is used for both layers of substrates, of which the one for MLine (i.e. above the ground) is 1.5 mm and the other (i.e. below the ground) is 0.2 mm. A thin substrate for the NFCs helps for better controlling the parasitics. With a 7.5 mm-wide MLine and a periodicity of 10 mm, the capacitance per unit-cell-length is 3 pF, and the effective permittivity is 2.97. Therefore, at least 1 pF is needed for achieving FW propagation, and about 1.2 c phase velocity can be achieved when −2.4 pF is loaded to the waveguide.

Fig. 2 presents the NFC schematic and the measurement results for the designed negative capacitor circuit. Linvill's negative impedance circuit is adopted for generating the negative capacitance [9]. Two cross-coupled transistors, Q1 and Q2, form a positive feedback for producing negative impedance. C3 is placed between the emitters of the transistors for impedance conversion. Additional resistors (R1) and capacitors (C1) are inserted between the base–collector connection to control the loop gain for guaranteeing stability. The negative capacitance is obtained from one of the DC decoupled base–collector connection. The circuit schematic and all the component values are illustrated in Fig. 2*a*. The designed circuit was fabricated and measured on a testing board, and the measurement result is shown in Fig. 2*b*, from which it can be seen that −2.8 pF is obtained about 100 MHz. Well-matched simulation and measurement results validate the design. Some deviation is due to the finite extra parasitics of the devices that cannot be fully included in the simulation. The negative resistive part is also shown in Fig. 2*b*, which appears to be negative after 110 MHz, indicating that the loaded unit cell cannot be unconditionally stable. However, as can be seen in the following Section, the 10-unit-cell cascaded structure presents stability with a 50 Ω load.

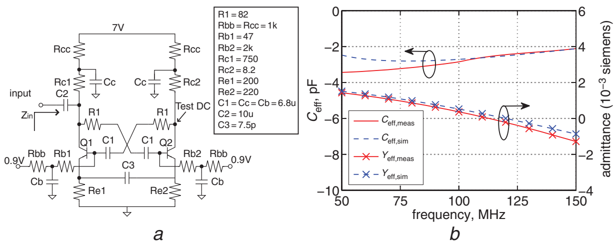

Fig. 2 *Schematic and measurement results of designed NFCs*

a Schematic
b Measurement results

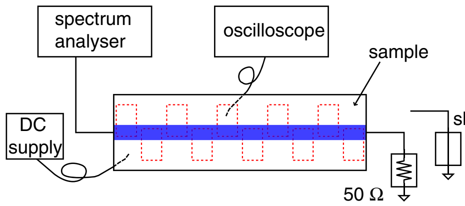

Fig. 3 *Measurement setup for investigating stability*

Measurements and discussion: The implemented −2.8 pF negative capacitor circuits have been incorporated into a 10-unit-cell NFC-loaded waveguide, as illustrated in Fig. 1. The stability of the fabricated waveguide was tested with the experimental setup as shown in Fig. 3, where one port of the waveguide is terminated with 50 Ω or short (i.e. 0 Ω). Three approaches were used for investigating the stability. First, a spectrum analyser (SA, Agilent N9010A) was used to terminate the other port of the waveguide. Spurious oscillation can be read out from measured spectra of the SA if the system is unstable. Secondly, DC biasing collector voltage at Q2 (see Fig. 2*a*) in one of the NFCs was monitored by an oscilloscope (Agilent MSO7104B) for low-frequency stability and DC-bias shift due to oscillation. Finally, the fabricated waveguide was measured with a vector network analyser (Agilent E5071C). The magnitude of the frequency response is applied to K-K relations for estimating its phase response [10], which is compared with the measured results.

The measurement results are presented in Fig. 4. When loaded with 0 Ω, the DC bias is averaged at 6.217 V, and spurious oscillations are found (see Fig. 4*a*), implying that the waveguide is unstable with short load. In contrast, Fig. 4*b* reveals an averaged DC voltage of 6.263 V and no oscillations from the measured spectrum for the 50 Ω load case, which indicates stability. The stability and causality have been further demonstrated by K-K relations as shown in Fig. 4*c*, where the calculated phase of *S*21 based on K-K relations matches the measurement. The retrieved and simulated phase velocities are exhibited in Fig. 4*d*, manifesting a FW propagation with the phase velocity of 1.2 c over the bandwidth of 80–120 MHz (within 10% variation), which is 1:1.5 bandwidth. The inset in Fig. 4*d* presents the detail of the retrieved phase velocity from measurements from 80 to 120 MHz. It is clear to see that the phase velocity reaches a maximum at about 100 MHz, where zero-slope phase velocity is obtained. As it is known that zero-slope phase velocity indicates non-dispersive propagation, thus it can be concluded that non-dispersive propagation can be achieved at about 100 MHz, which is impossible for any other conventional FW waveguide, such as a metallic rectangular waveguide. Moreover, the phase velocity varies <10% about 1.2 c, which can be sufficiently regarded as a low dispersive or non-dispersive band. The discrepancy between the simulation and the measurement results is due to the tolerance of the realistic components. The measurement results clearly demonstrate that the 10-unit-cell NFC-loaded waveguide is stable with, in particular, 50 Ω load, even though the waveguide is only conditionally stable.

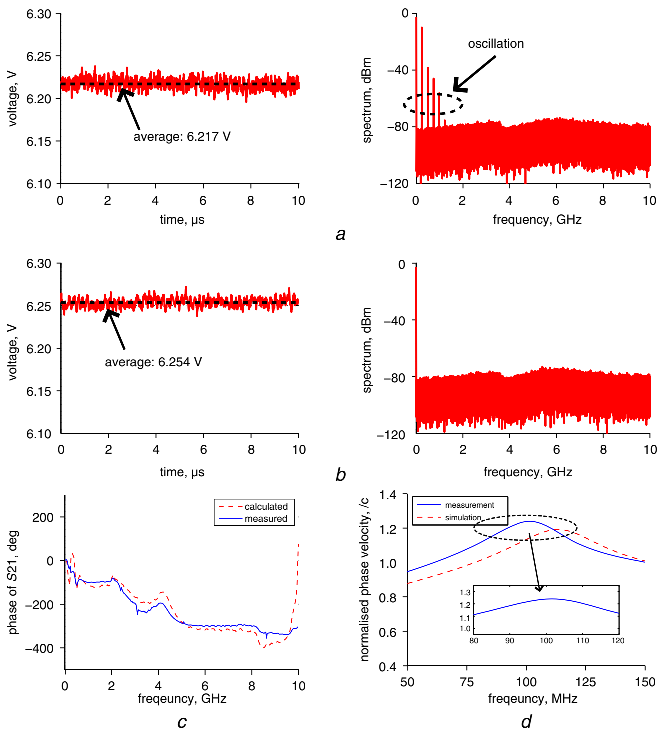

Fig. 4 *Measurement results*

a Measured DC voltage (left) and spectrum (right) when waveguide is terminated with short load
b DC voltage and spectrum for 50 Ω load case
c Comparison of measured phase *S*21 to calculated result based on K-K relations for 50 Ω load case
d Retrieved phase velocity in measurement and simulation for 50 Ω load case. Inset: Detail of retrieved phase velocity in measurement, indicating non-dispersive frequency point and low dispersion band

Conclusion: Although the NFC-loaded waveguide is potentially unstable, it is still possible to ensure the stability with specific loads, which makes the FW waveguide still realisable for applications. For demonstration, we have successfully designed a 10-unit-cell −2.8 pF NFC-loaded waveguide, which contains many more unit cells than the existing work, and have shown its stability with 50 Ω load in both the time and the frequency domain. The stability also has been verified by K-K relations. The measured stable and causal 10-unit-cell NFC-loaded waveguide presents non-dispersive propagation with a 1.2 c phase velocity over the bandwidth of 80–120 MHz or a 1:1.5 bandwidth, which shows the possibility of building stable electrically long FW waveguides for antennas and metasurfaces.

Acknowledgment: This work has been supported by the National Science Foundation under grant ECCS-1306055.

21 July 2014
doi: 10.1049/el.2014.2612
One or more of the Figures in this Letter are available in colour online.

J. Long and D.F. Sievenpiper (*Department of Electrical and Computer Engineering, Applied Electromagnetics Group, University of California at San Diego (UCSD), La Jolla, CA 92093, USA*)

E-mail: jilong@ucsd.edu

References

1 Hrabar, S., Krois, I., Bonic, I., and Kiricenko, A.: ‘Ultra-broadband simultaneous superluminal phase and group velocities in non-Foster epsilon-near-zero metamaterial’, *Appl. Phys. Lett.*, 2013, **102**, p. 054108
2 Long, J., Jacob, M.M., and Sievenpiper, D.F.: ‘Broadband fast-wave propagation in a non-Foster circuit loaded waveguide’, *IEEE Trans. Microw. Theory Tech.*, 2014, **62**, pp. 789–798
3 Sievenpiper, D.F.: ‘Superluminal waveguides based on non-Foster circuits for broadband leaky-wave antennas’, *IEEE Antennas Wirel. Propag. Lett.*, 2011, **10**, pp. 231–234
4 Sievenpiper, D.F., Jacob, M.M., and Long, J.: ‘Active electromagnetic structures, metamaterials, and antennas’. Proc. IEEE Int. Workshop on Antenna Technology (iWAT), Tuscon, AZ, USA, March 2012, pp. 289–292
5 Mirzaei, H., and Eleftheriades, G.V.: ‘An active artificial transmission line for squint-free series-fed antenna array applications’. Proc. European Microwave Conf. (EuMC), Manchester, UK, October 2011, pp. 503–506
6 Chen, P.-Y., Argyropoulos, C., and Alù, A.: ‘Broadening the cloaking bandwidth with non-Foster metasurfaces’, *Phys. Rev. Lett.*, 2013, **111**, p. 233001
7 Rengarajan, S.R., and White, C.R.: ‘Stability analysis of superluminal waveguides periodically loaded with non-Foster circuits’, *IEEE Antennas Wirel. Propag. Lett.*, 2013, **12**, pp. 1303–1306
8 Foster, R.M.: ‘A reactance theorem’, *Bell Syst. Tech. J.*, 1924, **3**, pp. 259–267
9 Linvill, J.G.: ‘Transistor negative-impedance converters’, *Proc. IRE*, 1953, **41**, pp. 725–729
10 Bechhoefer, J.: ‘Kramers–Kronig, Bode, and the meaning of zero’, *Am. J. Phys.*, 2011, **79**, pp. 1053–1059