Progress In Electromagnetics Research, Vol. 137, 117–127, 2013

NEW NEGATIVE COUPLING STRUCTURE FOR SUBSTRATE-INTEGRATED CAVITY RESONATORS AND ITS APPLICATION TO DESIGN OF AN ELLIPTIC RESPONSE FILTER

Kangho Lee, Tae-Hak Lee, Young-Sik Kim, and Juseop Lee*

Department of Computer and Communications Engineering, Korea University, Seoul 136-713, Korea

Abstract—This paper presents a new type of a negative coupling structure for designing elliptic-response filters with cross-coupling. The proposed coupling structure consists of short-circuited coupled transmission lines. Using the fact that insertion phase of the coupled line structure is different from that of an inductive iris, it is shown that the proposed coupling structure can be used as the negative coupling structure. In order to verify the proposed coupling structure, we designed a 4th-order cross-coupled elliptic-response bandpass filter with substrate integrated waveguide resonators. A pair of transmission zeros in measurement and simulation results validates that the proposed structure can be used as the negative coupling structure.

1. INTRODUCTION

As wireless communications systems have required tighter microwave filter specifications, a tremendous amount of studies has been devoted to developing new filter design theories and topologies [1–8]. Recently, studies on negative coupling structures have presented physical realization of frequency responses with transmission zeros that enhance the frequency selectivity. Shorted stub implemented in substrate-integrated waveguide (SIW) can be used to realize transmission zeros [9]. Asymmetric feeding transmission line can also create transmission zeros [10, 11]. It has been reported that T-shape unit in resonator can also be used to realize transmission zeros [12]. However, in most cases, the negative coupling is required to generate transmission zeros.

Received 20 January 2013, Accepted 5 February 2013, Scheduled 14 February 2013
* Corresponding author: Juseop Lee (juseoplee@gmail.com).

The insertion phase of a quarter-wavelength transmission line and that of a three-quarter-wavelength transmission line are 180° different from each other. Therefore, a three-quarter-wavelength transmission line can be used for negative coupling while a quarter-wavelength transmission line is used for positive coupling [13]. A pair of s-shape slots on the top and bottom conductor layers around via-holes have been reported to create negative coupling for substrate integrated waveguide resonators [14]. A meandered slot on one conductor layer between two substrate integrated waveguide resonators can also create negative coupling [15]. It has also been found that simply placing a strip line on the surface of the dielectric linkage between two physically linked dielectric resonators can produce negative coupling [16].

In this paper, we present a new negative inter-resonator coupling structure for substrate-integrated waveguide resonators. The proposed coupling structure uses coupled transmission lines. One end of each transmission line is short-circuited for negative coupling coefficients. For validation of the proposed negative coupling structure, a 4th-order cross-coupled resonator filter with an elliptic response is designed and measured. The measured response shows a pair of transmission zeros, which validates the proposed negative coupling structure.

2. COUPLING STRUCTURE AND FILTER DESIGN

Figure 1 shows the coupling routing diagram of a 4th-order elliptic-response bandpass filter with cross coupling between resonators 1 and 4. It has four inter-resonator coupling structures, and an elliptic-response filter can be designed if one of the four inter-resonator coupling value is negative. In this paper, the filter has negative

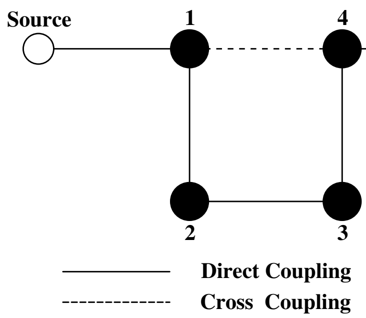

Figure 1. The coupling routing diagram of a 4th-order elliptic-response bandpass filter. In this work, the filter is designed to have negative coupling coefficient between resonators 1 and 4.

coupling between resonators 1 and 4. The transmitted power ratio of a 4th-order filter is given by

$$|t(S)|^2 = \frac{1}{1 + \epsilon^2 \frac{\left|\Pi_{k=1}^{N}(S-S_{rk})\right|^2}{\left|\Pi_{j=1}^{T}(S-S_{tj})\right|^2}} \tag{1}$$

where $S = j\Omega$ and Ω is normalized angular frequency. S_r and S_t are reflection zeros and transmission zeros, respectively, in the normalized complex frequency domain. N is the number of reflection zeros, which means the order of filter, and T is the number of transmission zeros. ϵ is a ripple constant which defines the magnitude of the ripple in the passband, and it is given by

$$\epsilon = \sqrt{\frac{1}{10^{R_1/10} - 1} \frac{1}{|K(j\Omega_1)|^2}} \tag{2}$$

where R_1 represents the maximum return loss in the passband, and Ω_1 is referred to as the cutoff frequency in the normalized frequency domain.

To verify proposed negative coupling structure, we design an elliptic-response filter with 20 dB equi-ripple return loss in the passband. The frequency response in the normalized frequency domain is shown in Fig. 2. Using the conventional filter synthesis

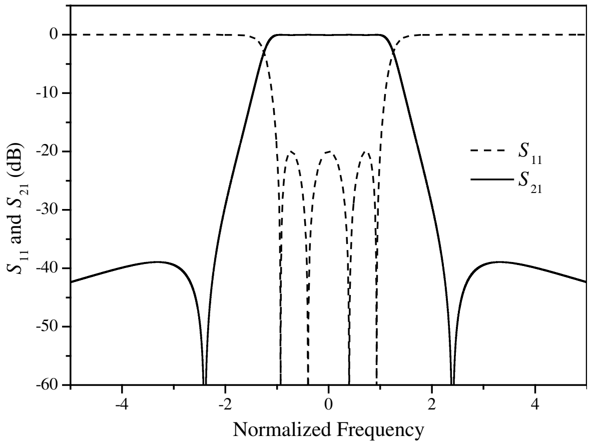

Figure 2. The frequency response of the filter in the normalized frequency domain.

process [17, 18], we can obtain the coupling matrix, and it is given by

$$\mathbf{M} = \begin{bmatrix} & \mathbf{S} & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{L} \\ \mathbf{S} & 0 & 1.0272 & 0 & 0 & 0 & 0 \\ \mathbf{1} & 1.0272 & 0 & 0.8860 & 0 & -0.1123 & 0 \\ \mathbf{2} & 0 & 0.8860 & 0 & 0.7446 & 0 & 0 \\ \mathbf{3} & 0 & 0 & 0.7446 & 0 & 0.8860 & 0 \\ \mathbf{4} & 0 & -0.1123 & 0 & 0.8860 & 0 & 1.0272 \\ \mathbf{L} & 0 & 0 & 0 & 0 & 1.0272 & 0 \end{bmatrix} \quad (3)$$

For verification of the short-circuited coupled transmission line coupling structure, we designed a substrate-integrated waveguide resonator filter with the proposed structure between resonators 1 and 4. Fig. 3 shows a layer-by-layer filter structure. Cylindrical resonators are embedded in 3.175 mm thick TMM3 substrate ($\epsilon_r = 3.27, \tan\delta = 0.0012$). The side walls of the resonators are established by plated via-holes whose radius is 0.4 mm. The radius of the cavity resonator is defined by the distance between the center of the cavity and the center of one of the via-holes. The radius of resonators is designed to be 24.63 mm. The irises are used to form the inter-resonator coupling structures except coupling between resonators 1 and 4.

Microstrip transmission lines are plated on a 0.508 mm thick RO5880 substrate ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$). Input and output transmission lines for external coupling are shorted above the coupling apertures for the maximum magnetic coupling.

Figures 4 and 5 show typical magnitude and phase responses of the transmission coefficient of two weakly-excited resonators coupled by

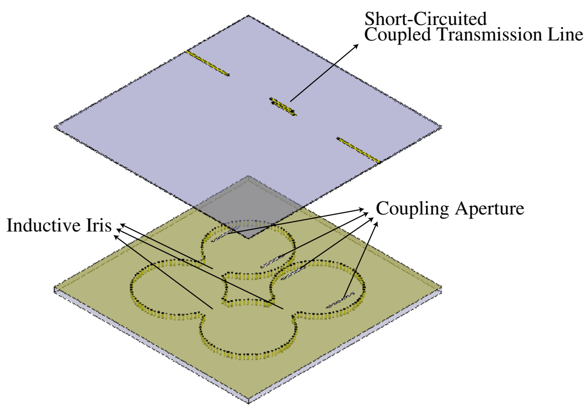

Figure 3. A layer-by-layer structure of the elliptic-response filter with substrate-integrated waveguide resonators.

the inductive iris and the proposed structure (short-circuited coupled transmission lines), respectively. It is shown that there is 180° phase difference between iris coupling and short-circuited coupled transmission line coupling, which allow us to employ short-circuited coupled transmission line coupling as the negative one while we use the iris coupling as the positive one. This is the reason that the coupled transmission line structure with shorted ends is used between resonators 1 and 4 while irises are used other inter-resonator coupling.

To determine the coupling coefficient, simulations of two weakly-excited resonator structures were carried out using Ansoft HFSS. Fig. 6(a) shows the coupling coefficient of the inductive iris between two substrate-integrated waveguide resonators. The coupling coefficient, k, is given by [19]

$$k = \frac{f_b^2 - f_a^2}{f_b^2 + f_a^2} \tag{4}$$

where f_b and f_a represent higher and lower resonant frequencies of the coupled resonators, respectively. The relationship between the de-normalized coupling coefficient, k, and the normalized coupling coefficient, M, is given by

$$k = \Delta f \cdot M \tag{5}$$

where Δf is the fractional bandwidth. It is shown that the iris coupling is determined only by the width of the iris with the given height. On the other hand, the proposed coupling structure has more design

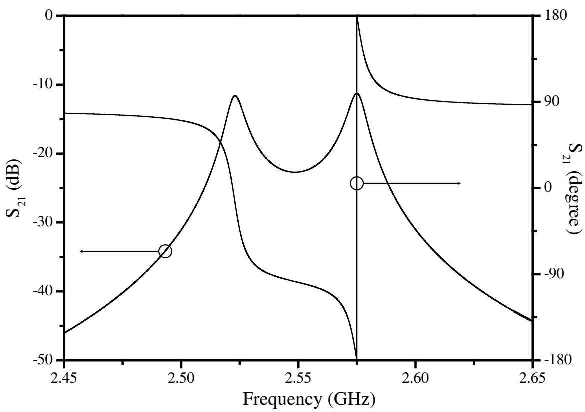

Figure 4. Magnitude and phase responses of the transmission coefficient of two weakly-excited resonators coupled by the n inductive iris.

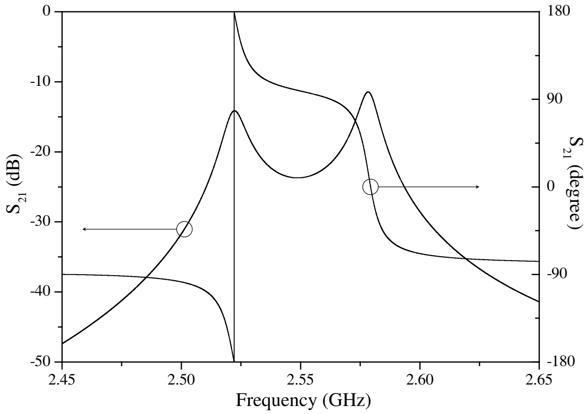

Figure 5. Magnitude and phase responses of the transmission coefficient of two weakly-excited resonators coupled by the short-circuited coupled transmission line.

parameters that determine the coupling coefficient. Fig. 6(b) shows the coupling coefficient of the proposed coupling structure between the two resonators for the case that the width of the coupling apertures is 16 mm. It is shown that the magnitude of the coupling coefficient increases as the length of the coupled transmission lines and the difference between even- and odd-mode impedances increases.

Figure 7 shows the coupling coefficient of the input/output external coupling structure. In this case, the relationship between the de-normalized coupling coefficient, k, and the normalized coupling coefficient, M, is given by

$$k = \sqrt{\Delta f} \cdot M \tag{6}$$

It is shown that the coupling coefficient is determined by the width of the coupling aperture with the given height.

To verify the fact that the proposed coupling structure can be used as the negative coupling structure for the substrate-integrated waveguide resonator, we designed an elliptic-response filter that requires the negative coupling structure. The target center frequency and bandwidth are 2.55 GHz and 70 MHz, respectively. The physical dimensions of the external coupling structures and the positive inter-resonator coupling structures were determined based on the design graphs shown in Fig. 6(a) and Fig. 7. Similarly, the negative coupling between the resonators 1 and 4 can be designed based on Fig. 6(b). Since the required coupling coefficient is -0.0031, the negative coupling structure has been designed in such a way that the even- and odd-mode impedances are 64.04 Ω and 39.04 Ω, respectively, and the length is 12 mm.

Fig. 8 shows detailed physical dimensions of the microstrip line structures and coupling apertures on the conductor layer between the two dielectrics. All aperture heights are fixed at 1 mm. For coupled transmission line to have desired even- and odd-mode characteristic impedance, width of 1.339 mm microstrip lines are used and each line is separated from each other by 0.183 mm.

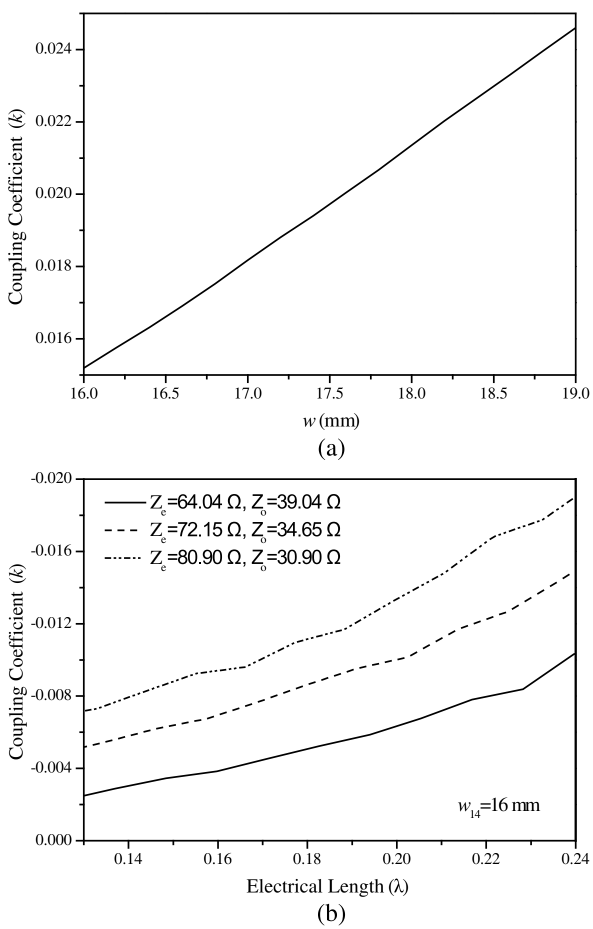

Figure 6. Inter-resonator coupling coefficient. (a) Inductive iris, (b) the proposed negative coupling structure (short-circuited coupled transmission line structure.)

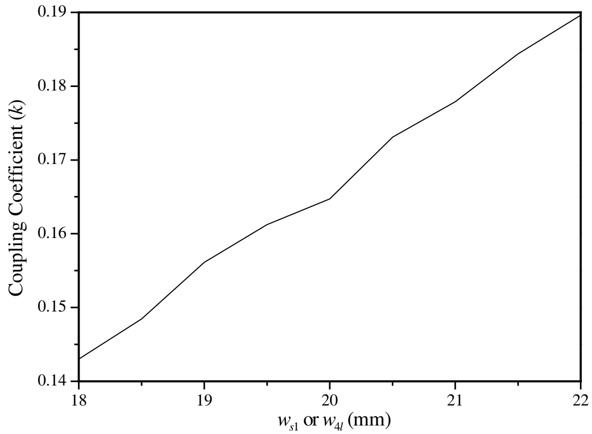

Figure 7. Coupling coefficient of the external coupling.

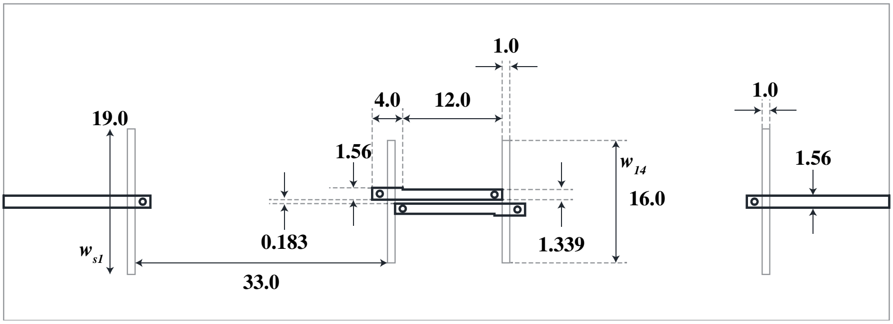

Figure 8. Physical dimensions of the microstrip line structures and coupling apertures on the conductor layer between the two dielectrics. Thick and thin solid line represent microstrip line structures and coupling apertures, respectively. All dimensions are in mm.

3. FABRICATION AND MEASUREMENT

Figure 9 shows photographs of the top and bottom views of the fabricated filter. Fabricated microstrip transmission lines are shown in Fig. 9(a), and Fig. 9(b) shows via holes that compose the side walls of the substrate-integrated waveguide resonators. Fig. 10 compares the measured result with the simulation. Both the measured and simulated results exhibit the prescribed frequency response with a pair of transmission zeros. The measured and simulated insertion losses are 1.7 dB and 1.6 dB, respectively. The next higher-order mode is

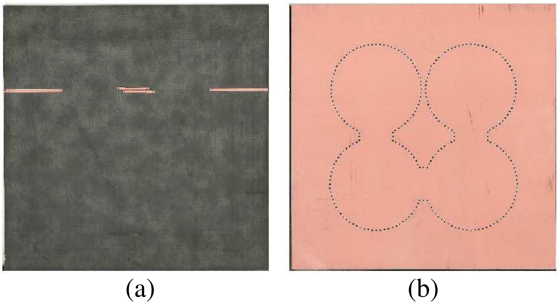

Figure 9. Photograph of the 4th-order elliptic-response filter. (a) Upper side, (b) lower side.

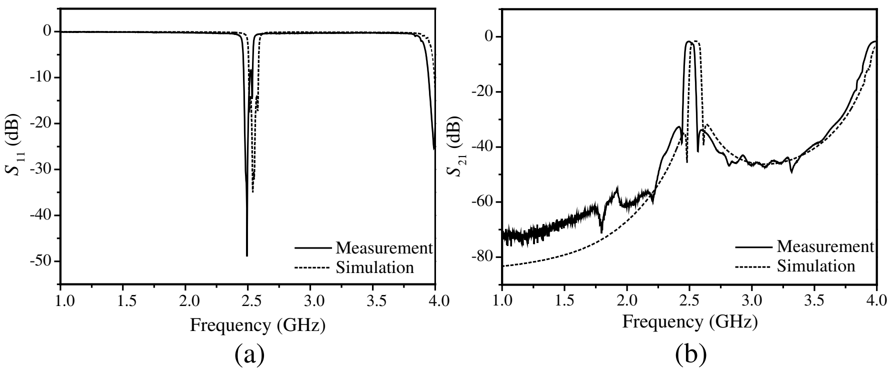

Figure 10. The magnitude response of the 4th-order elliptic-response filter with proposed inter-resonator coupling structure obtained by simulation and measurement. (a) Reflection coefficient, (b) transmission coefficient.

observed around 4.0 GHz in both the measurement and simulation. It is of note that the existence of a pair of the transmission zeros close to the passband verifies that the proposed structure is the negative coupling structure. A small discrepancy including the frequency shift between the measured and simulated frequency responses can be attributed to fabrication errors. The proposed negative coupling structure can also be applied to the air cavity resonator.

4. CONCLUSIONS

In this paper, a new type of negative inter-resonator coupling structure is proposed. The coupling structure employs coupled transmission line. The end of each transmission line is short-circuited, which allows the coupling structure to have 180° different phase compared to the coupling which uses iris.

In order to verify the proposed coupling structure, we designed a 4th-order elliptic-response filter which requires negative coupling. In the filter structure, inductive irises were used for the positive coupling, while the coupled transmission line structure was used for the negative one. The measured response showed a good agreement with a simulation result, which validates that the proposed coupling structure can be used for the negative coupling.

ACKNOWLEDGMENT

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science, and Technology(2012R1A1A1004665).

REFERENCES

1. Gulgowski, J. and J. J. Michalski, "The analytic extraction of the complex-valued coupling matrix and its application in the microwave filter modeling," *Progress In Electromagnetics Research*, Vol. 130, 131–151, 2012.
2. Wang, R., J. Xu, C. L. Wei, M.-Y. Wang, and X.-C. Zhang, "Improved extraction of coupling matrix and unloaded Q from S-parameters of lossy resonator filters," *Progress In Electromagnetics Research*, Vol. 120, 67–81, 2011.
3. Xiao, K., L. F. Ye, F. Zhao, S.-L. Chai, and J. L.-W. Li, "Coupling matrix decomposition in designs and applications of microwave filters," *Progress In Electromagnetics Research*, Vol. 117, 409–423, 2011.
4. Ho, M.-H. and P.-F. Chen, "Suspended substrate stripline bandpass filters with source-load coupling structure using lumped and full-wave mixed approach," *Progress In Electromagnetics Research*, Vol. 122, 519–535, 2012.
5. Chaudhary, G., Y. Jeong, K. Kim, and D. Ahn, "Design of dual-band bandpass filters with controllable bandwidths using new mapping function," *Progress In Electromagnetics Research*, Vol. 124, 17–34, 2012.
6. Kuo, J.-T. and S.-W. Lai, "New dual-band bandpass filter with wide upper rejection band," *Progress In Electromagnetics Research*, Vol. 123, 371–384, 2012.

7. Vegesna, S. and M. A. Saed, "Compact two-layer microstrip bandpass filters using broadside-coupled resonators," *Progress In Electromagnetics Research B*, Vol. 37, 81–102, 2012.
8. Mohan, A., S. Singh, and A. Biswas, "Generalized synthesis and design of symmetrical multiple passband filters," *Progress In Electromagnetics Research B*, Vol. 42, 115–139, 2012.
9. Jedrzejewski, A., L. Leszczynska, and M. Mrozowski, "Zero-pole approach to computer aided design of in-line SIW filters with transmission zeros," *Progress In Electromagnetics Research*, Vol. 131, 517–533, 2012.
10. Kuo, J.-T., S.-C. Tang, and S.-H. Lin, "Quasi-elliptic function bandpass filter with upper stopband extension and high rejection level using cross-coupled stepped-impedance resonators," *Progress In Electromagnetics Research*, Vol. 114, 395–405, 2011.
11. Zhu, Y.-Z., Y.-J. Xie, and H. Feng, "Novel microstrip bandpass filters with transmission zeros," *Progress In Electromagnetics Research*, Vol. 77, 29–41, 2007.
12. Xu, Z.-B., J. Guo, C. Qian, and W.-B. Dou, "A novel quasi-elliptic waveguide transmit reject filter for Ku-band VSAT transceivers," *Progress In Electromagnetics Research*, Vol. 117, 393–407, 2011.
13. Kajfez, D. and P. Guillon, *Dielectric Resonators*, Noble Publishing Corp., Atlanta, GA, 1998.
14. Chen, X.-P. and K. Wu, "Substrate integrated waveguide cross-coupled filter with negative coupling structure," *IEEE Trans. Microwave Theory Tech.*, Vol. 56, No. 1, 142–149, Jan. 2008.
15. Shen, W., L.-S. Wu, X.-W. Sun, W.-Y. Yin, and J.-F. Mao, "Novel substrate integrated waveguide filters with mixed cross coupling (MCC)," *IEEE Microwave Wireless Compon. Lett.*, Vol. 19, No. 11, 701–703, Nov. 2009.
16. Zhang, R. and R. R. Mansour, "Low-cost dielectric-resonator filters with improved spurious performance," *IEEE Trans. Microwave Theory Tech.*, Vol. 55, No. 10, 2168–2175, Oct. 2007.
17. Williams, A. E., "A four-cavity elliptic waveguide filter," *IEEE Trans. Microwave Theory Tech.*, Vol. 18, No. 12, 1109–1114, Dec. 1970.
18. Kudsia, C. M., "A generalized approach to the design and optimization of symmetrical microwave filters for communications systems," Ph.D. dissertation, Dept. Eng., Concordia Univ., Quebec, QC, Canada, 1978.
19. Hong, J.-S. and M. J. Lancaster, *Microstrip Filter for RF/Microwave Applications.*, Wiley, New York, 2001.