Utilizing Nonlinearity in a Superconducting NbN Stripline Resonator for Radiation Detection

Eran Segev, Baleegh Abdo, Oleg Shtempluck, and Eyal Buks

***Abstract*—We study a microwave superconducting stripline resonator made of NbN on a sapphire substrate. A radiation detector (RD) having a thin meander shape is integrated into the resonator. We harness an extremely strong nonlinear instability occurring in the device in order to enhance its sensitivity to infrared radiation impinging on the RD. Characterization measurements yield a noise equivalent power of 34 $\mathrm{fW}/\sqrt{\mathrm{Hz}}$ at a modulation frequency of 7.74 GHz. Such a device may be exploited for fast and sensitive radiation detection.**

I. Introduction

ULTRA-FAST and sensitive radiation detection is a key enabling element in various fields of research, such as biofluorescence detection, quantum cryptography and more. Detectors based on a thin layer of superconducting NbN are widely employed, due to their superior characteristics in terms of quantum efficiency and dark counts [1]. Switching time in superconductors is usually limited by the relaxation process of high-energy quasi-particles, also called 'hot-electrons', giving their energy to the lattice, and recombining to form Cooper pairs. Recent experiments with NbN photodetectors have demonstrated an intrinsic switching time on the order of 30 ps and a counting rate exceeding 2 GHz (see [1] and references therein). An on-going effort is put on improving the performances of these sensors by further increasing quantum efficiency and reducing the rate of dark counts [2].

We employ a novel configuration in which a radiation detector (RD) is implemented as an integrated part of a microwave superconducting NbN stripline resonator. Absorption of radiation by the RD results in a detectable shift in the resonance frequency of the resonator and a modified damping rate. Quasi-static resonance frequency shift by optical radiation [3]–[5], or high-energy particles [6], [7] was already demonstrated in superconducting resonators. Resonance frequency tuning [8] and switching [9] as well as optical and microwave signal mixing [10], [11] were demonstrated in normal-conducting GaAs microstrip ring resonators. In a previous publication [12] we have studied the response of our device to infrared (IR) illumination impinging on the RD. To characterize the response time of the system we have modulated the impinging optical power with a varying frequency and measured the response of the device as a function of the modulation frequency and the illumination intensity. The device has shown an ultra-fast and sensitive response to such an excitation in a narrow band around twice the modulation frequency [13].

In another recent study we have reported on several extreme nonlinear phenomena that have been found in our devices. In these experiments a monochromatic pump tone, at a frequency close to one of the resonance frequencies, is injected into the resonator and the reflected power off the resonator is measured. We have discovered that there is a certain zone in the pump frequency - pump amplitude plane, in which a novel self-sustained modulation (SM) of the reflected power occurs [14]. The modulation frequency varies between several to tenth of megahertz. According to a theoretical model, the SM originates from a thermal instability in the RD [15]. Near the onset of the SM phenomenon the device exhibits a chaotic like behavior and is characterized by a strong nonlinear behavior [16]. Intermodulation (IM) characterization performed in this zone yields an extremely high gain (about 30dB), which is accompanied by a very strong noise squeezing (about 45dB squeezing factor) and period doubling of various orders [16].

In this work we investigate the correlation between the response of the device to power-modulated IR light and the SM and IM phenomena. We find that the strong responsitivity occurs near the power threshold of the SM, where the device also exhibits the strong IM gain. Our novel radiation detector may have some important applications in both basic science and technology. It may be exploited to demonstrate some important quantum phenomena in the microwave region, such as experimental observation of the so called dynamical Casimir effect [13], [17]. These effects may also allow some intriguing technological applications such as sensitive radiation sensing, single photon detection [6] and more.

This paper is organized as follows. First a brief overview of the device and the experimental setup is given. Then the fundamental SM phenomenon and the accompanying IM phenomenon are described. Finally the response of the device to a power-modulated IR illumination is demonstrated and its correlation to the abovementioned phenomena is emphasized.

II. Circuit Design and Experimental Setup

The experimental setup is schematically depicted in Fig. (1a). The resonator is stimulated with a monochromatic pump tone at frequency $f_{\mathrm{pump}} = 3.71$ GHz, which coincides with the second resonance frequency of the resonator, and the reflected power off the resonator is amplified at room temperature and measured

Manuscript received August 16, 2006; revised January 17, 2007. This work was supported by the German Israel Foundation under Grant 1-2038.1114.07, the Israel Science Foundation under Grant 1380021, the Deborah Foundation, the Poznanski Foundation, and MAFAT.

The authors are with the Department of Electrical Engineering and Microelectronics Research Center, Technion, Haifa 32000, Israel (e-mail: segeve@tx.technion.ac.il).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2007.897723

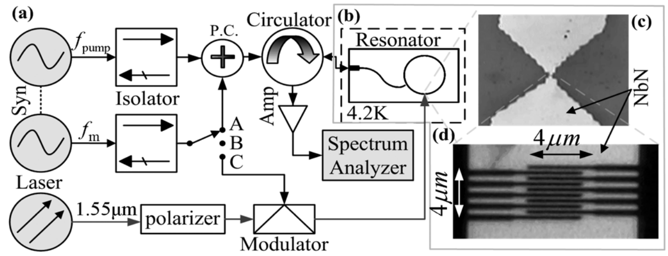

Fig. 1. (a) Measurement setup. (b) A simplified circuit layout of the resonator. ((c) and (d)) Optical microscope images showing the meander-shaped RD.

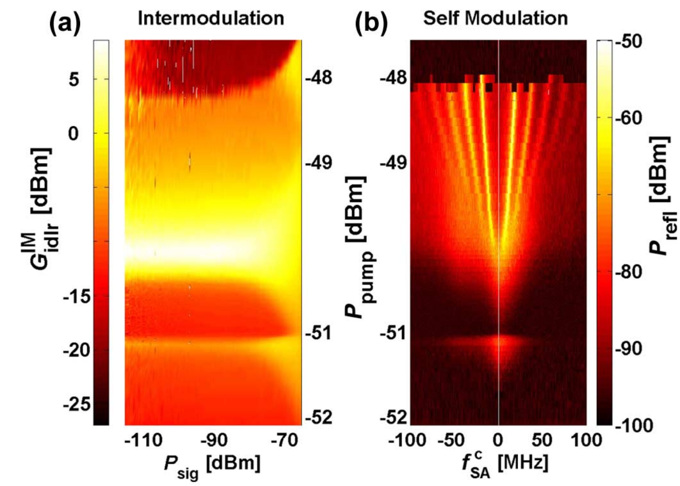

Fig. 2. (a) IM Idler gain as a function of the input Pump and input Signal powers. (b) Typical SM measurement, showing the reflected power off the resonator as a function of the measured frequency and the pump power. Reflected power values below −100 dBm and above −50 dBm are truncated to improve visibility.

using a spectrum analyser (SA). In addition, a second synthesizer, phased-locked with the first one, having a frequency f_{m}, may be used to stimulate the resonator with another monochromatic microwave tone. Alternatively, it may be used to drive a Mach-Zender modulator, which modulates the power of an IR laser light (wavelength 1550 nm) guided to the RD using a fiber optic cable. All measurements are carried out while the device is fully immersed in liquid Helium.

The resonator is designed to allow fast modulation of its resonance frequencies by external or internal (Joule self-heating) perturbations [12], and takes advantage of recent progress in the field of superconducting single photon detectors. A simplified circuit layout of the device is illustrated in Fig. (1b). The resonator is designed as a stripline ring, having a characteristic impedance of 50 Ω. It is composed of 8-nm-think NbN film on a sapphire wafer. The first few resonance frequencies fall within the range of 2–8 GHz. A feedline, weakly coupled to the resonator, is employed for delivering the input and output signals. A RD is integrated into the structure of the ring. Its angular location (Fig. (1b)), relative to the feedline coupling location, maximizes the RF current amplitude flowing through it in one of the resonance modes, and thus maximizes its coupling to that mode. The RD has meander shape geometry (Fig. (1d)) that consists of nine strips. Each strip has a characteristic area of $0.15 \times 4\ \mu\mathrm{m}^2$ and the strips are separated one from another by approximately 0.25 μm [18]. Further design considerations, fabrication details as well as calculation of normal modes can be found elsewhere [12].

We employ the following detection method. An optical signal impinging on the RD generates a hotspot, which is basically a small island of normal-conducting area, with a relatively high temperature, surrounded by a superconducting domain [19]. If the RD is biased into sub-critical conditions then the hotspot further expends and consequently the impedance of the RD is substantially modified [20]. Due to the strong coupling between the RD and the open ring stripline this results in an easily-detectable resonance shift [6]. Subsequently, the excess heat is quickly transferred to the substrate and the device relaxes back to its original state.

III. Experimental Results

The SM phenomenon occurs in a certain zone in the $f_{\mathrm{pump}} - P_{\mathrm{pump}}$ plane, where P_{pump} is the input power. In that zone the resonator exhibits no steady state response. A detailed experimental study of the SM, as well as a theoretical model which attributes this effect to a thermal instability in the RD, are elaborated elsewhere [14], [15]. Here we only briefly describe the dependence of the SM on the stimulating pump power. Fig. (2b) shows typical experimental results of the SM phenomenon in the frequency domain. It plots a color map of the reflected power off the resonator as a function of the input pump power P_{pump} and the measured SA frequency, centralized on the resonance frequency $f_0 = 3.71$ GHz ($f_{\mathrm{SA}}^{\mathrm{c}} = f_{\mathrm{SA}} - f_0$), while the resonator is stimulated with a single monochromatic tone at $f_{\mathrm{pump}} = f_0$. Outside a certain range of input pump powers ($P_{\mathrm{pump}} \lesssim -51.5\ \mathrm{dBm} \cup P_{\mathrm{pump}} \gtrsim -48\ \mathrm{dBm}$) the behavior of the resonator is linear, namely, the power reflected off the resonator contains a single spectral component at the frequency of the stimulating pump tone. On the other hand, inside this power range regular SM of the power reflected off the resonator occurs. It is realized by rather pronounce and equally spaced sidebands, which extend at both sides of the resonance frequency. The SM frequency, which is defined as the frequency difference between the pump and the primary sidebands on both sides of the pump frequency, increases as the pump power increases, and varies in the range of 5–25 MHz [15]. At the lower power threshold, where the SM starts, the resonator's response desists being linear and experiences a strong amplification of the noise floor (noise rise) over a rather large frequency band, especially around the resonance frequency itself. This noise rise can be explained in terms of nonlinear dynamics theory, as it predicts the occurrence of strong noise amplification near a threshold of instability [21]. The expected amplification is linearly unbounded and saturates only due to nonlinear terms of higher order [22].

Several additional nonlinear phenomena, such as IM, phase sensitive deamplification and period doubling of various orders manifest at the lower SM power threshold [16]. The IM, which is herein briefly described, reveals a powerful amplification mechanism. IM, as measured in our devices, is the result of two unequal tones, called Pump and Signal, being mixed together by

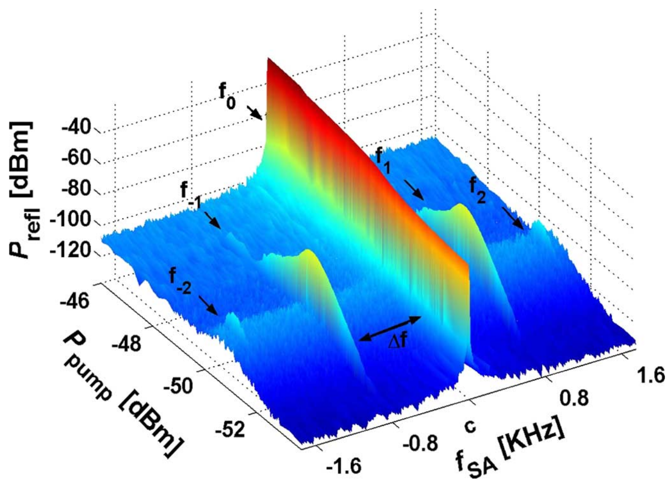

Fig. 3. Measured response of the resonator to a modulated IR illumination at a modulation frequency $f_{\rm m} \approx 7.74\ {\rm GHz}$.

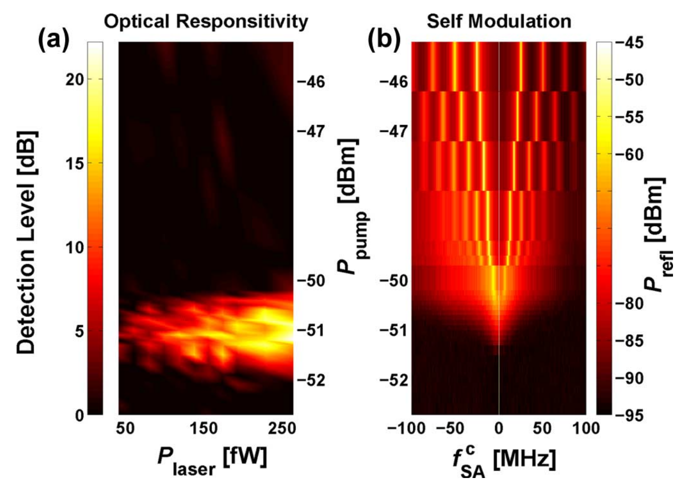

Fig. 4. (a) Measured response to power-modulated IR illumination normalized by the noise floor. (b) SM measurement. Reflected power values below -95 dBm and above -45 dBm are truncated to improve visibility.

the nonlinear system, which produces additional tones at frequencies that are linear combinations (integer multiples) of both [23]. The Pump and Signal tones have closely spaced frequencies $f_{\rm pump} = f_0$ and $f_{\rm m} = f_{\rm pump} + \Delta f$, where $\Delta f = 800\ {\rm Hz}$ is much smaller than the resonance bandwidth. The largest IM products appear as a result of a third order IM mixing since usually, the second order mixing products do not coincide with any natural resonance frequency of the resonator [24]. The third order mixing produces are two tones, known as Signal and Idler. The frequency of the former coincides with the input Signal frequency and the Idler is measured at frequency $f_{\rm Idler} = f_{\rm pump} - \Delta f$. Theory predicts that, as the input pump tone drives the resonator to the edge of instability, both the Signal and the Idler tones undergo equally large amplification [25].

The strength of the IM nonlinearity can be qualitatively characterized by calculating the Idler gain, defined as the ratio between the output power of the Idler component and the input Signal power. Fig. (2a) shows this characterization, as was measured simultaneously with the SM measurement presented in Fig. (2b). The area of strong amplification is indicated by bright shaded colors, where a maximum amplification of 8.5 dB is measured. The strong amplification is measured at the lower SM power threshold and thus indicates the strong correlation between the two phenomena. To emphasize the strength of the amplification we note that usually, no amplification greater than unity (0 dB) is achieved in IM measurements with superconducting resonators [24], [25].

Fig. 3 shows typical detection response of our device to a power-modulated IR illumination as a function of the driving microwave pump power. The device is stimulated with a single monochromatic pump tone at $f_{\rm pump} = f_0$ and the reflected power is measured. In addition the RD is illuminated by a power-modulated IR light, having an average power of 21 pW, and a modulation frequency at slightly above twice the pump frequency $f_{\rm m} = 2f_{\rm pump} + \Delta f$, where $\Delta f = 800\ {\rm Hz} \ll f_{\rm pump}$. As was explained above, the power-modulated IR illumination causes a parametric excitation of the driven mode. Consequently a mixing between the optical signal and the microwave pump tone occurs [26], which results in new spectral components at frequencies which are linear combinations of $f_{\rm pump}$ and $f_{\rm m}$. The reflected power at the measured frequency band shows five such distinguished tones. The strongest one, labeled as f_0, is the reflected spectral component at the frequency of the stimulating pump tone $f_{\rm pump}$. The other four tones are found at frequencies $f_n = f_{\rm pump} + n\Delta f$. For example, f_1 and f_{-1} tones results from second $(f_1 = f_{\rm m} - f_{\rm pump})$ and forth $(f_{-1} = 3f_{\rm pump} - f_{\rm m})$ order mixing respectively. Although the amplitudes of the mixing products of higher orders are relatively low, their presence implies the strength of the nonlinearity. One clearly notes that strong detection only occurs in a well defined power range of the pump tone. At this power range the detected signal as well as the input noise are being amplified, but the signal to noise ratio is well above unity.

Fig. (4a) plots the power of the f_1 tone above the surrounding noise floor, as a function of the optical illumination power and the microwave pump power. High sensitivity is indicated by bright shaded colors. We define the NEP as the lowest possible illumination power in which the f_1 tone can be distinguished from the surrounding noise floor. The illumination power employed in this measurement ranges between 50–250 fW, where the measured noise equivalent power (NEP) is 34 ${\rm fW}/\sqrt{\rm Hz}$. In order to test the correlation between the response of the device to IR illumination and the abovementioned nonlinear phenomena a simultaneous SM measurement is shown in Fig. (4b). This measurement result is similar but not identical to the one shown in Fig. (2b), as the two measurements were taken during different cooldown cycles. The comparison between the two panels of Fig. 4 shows that the response of the device to IR illumination is correlated to the SM phenomenon. As expected high sensitivity is achieved slightly below the first SM power threshold, where the RD is biased to sub-critical conditions, and consequently its sensitivity to external perturbations is relatively high. Moreover, the relatively fast response, which is demonstrated in this measurement, indicates that thermal relaxation time in the RD is relatively short [1].

IV. Conclusion

Our device exhibits an extreme nonlinear behavior, which is the result of a carefully designed integration between a superconducting resonator and a thin and narrow meander RD. We show that when the resonator is driven to the edge of instability it experiences a strong enhancement in its response to a power-modulated monochromatic IR illumination impinging on the meander strip. A NEP of 34 $\mathrm{fW}/\sqrt{\mathrm{Hz}}$ is measured in a narrow band around a modulation frequency of 7.74 GHz.

References

[1] G. N. Goltsman, A. Korneev, I. Rubtsova, I. Milostnaya, G. Chulkova, O. Minaeva, K. Smirnov, B. Voronov, W. Sysz, A. Pearlman, A. Verevkin, and R. Sobolewski, “Ultrafast superconducting single-photon detectors for near-infrared-wavelength quantum communications,” *Phys. Status Solidi C*, vol. 2, no. 5, pp. 1480–1488, 2005.

[2] J. Kitaygorsky, J. Zhang, A. Verevkin, A. Sergeev, A. Korneev, V. Matvienko, P. Kouminov, K. Smirnov, B. Voronov, G. Goltsman, and R. Sobolewski, “Origin of dark counts in nanostructured NbN single-photon detectors,” *IEEE Trans. Appl. Superconduct.*, vol. 15, no. 2, pp. 545–548, Jun. 2005.

[3] S. Cho and C.-S. Son, “Modulation of the resonance frequency of superconducting microwave resonators,” *IEEE Trans. Appl. Superconduct.*, vol. 13, no. 2, pp. 3659–3662, Jun. 2003.

[4] S. Cho and C.-S. Son, “Observation of bolometric optical response in superconducting microwave meander lines,” *J. Appl. Phys.*, vol. 84, no. 10, pp. 5657–5661, Nov. 1998.

[5] M. Tsindlekht, M. Golosovsky, H. Chayet, and D. Davidov, “Frequency modulation of the superconducting parallel-plate microwave resonator by laser irradiation,” *Appl. Phys. Lett.*, vol. 65, no. 22, pp. 2875–2877, Nov. 1994.

[6] P. K. Day, H. G. LeDuc, B. A. Mazin, A. Vayonakis, and J. Zmuidzinas, “A broadband superconducting detector suitable for use in large arrays,” *Nature*, vol. 425, pp. 817–821, Oct. 2003.

[7] R. Wedenig, T. Niinikoski, P. Berglund, J. K. R. Inen, L. Costa, M. Valtonen, R. Linna, J. Salmi, H. SeppaK, and I. Suni, “Superconducting NbN microstrip detectors,” *Nucl. Instrum. Methods Phys. Res. A*, vol. 443, no. 3, pp. 646–663, Sep. 1999.

[8] K. Chang, S. Martin, F. Wang, and J. L. Klein, “On the study of microstrip ring and varactor-tuned ring circuits,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, no. 12, pp. 1733–1739, Dec. 1987.

[9] T. S. Martin, F. Wang, and K. Chang, “Theoretical and experimental investigation of novel varactor-tuned switchable microstrip ring resonator circuits,” *IEEE Trans. Microwave Theory Tech.*, vol. 36, no. 12, pp. 1733–1739, Dec. 1988.

[10] J.-C. Lee, H. F. Taylor, and K. Chang, “Degenerate parametric amplification in an optoelectronic GaAs CPW-to-slotline ring resonator,” *IEEE Microwave Guided Wave Lett.*, vol. 7, no. 9, pp. 267–269, Sep. 1997.

[11] G. K. Gopalakrishnan, B. W. Fairchild, C. L. Yeh, C.-S. Park, K. Chang, M. H. Weichold, and H. F. Taylor, “Experimental investigation of microwave-optoelectronic interactions in a microstrip ring resonator,” *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 12, pp. 2052–2060, Dec. 1991.

[12] E. Arbel-Segev, B. Abdo, O. Shtempluck, and E. Buks, “Fast resonance frequency optical modulation in superconducting stripline resonator,” *IEEE Trans. Appl. Superconduct.*, vol. 16, no. 3, p. 1943, Sep. 2006.

[13] E. Segev, B. Abdo, O. Shtempluck, and E. Buks, Towards Experimental Study of the Dynamical Casimir Effect 2006, arXiv:quant-ph/0606099.

[14] E. Segev, B. Abdo, O. Shtempluck, and E. Buks, “Novel Self-Sustained Modulation in Superconducting Stripline Resonators,” 2006, arXiv: cond-mat/0607259.

[15] E. Segev, B. Abdo, O. Shtempluck, and E. Buks, “Thermal Instability and Self-Sustained Modulation in Superconducting NbN Stripline Resonators,” 2006, arXiv: cond-mat/0607261.

[16] E. Segev, B. Abdo, O. Shtempluck, and E. Buks, “Extreme Nonlinear Phenomena in NbN Superconducting Stripline Resonators,” 2006, arXiv: cond-mat/0607262.

[17] V. V. Dodonov and A. B. Klimov, “Generation and detection of photons in a cavity with a resonantly oscillating boundary,” *Phys. Rev. A*, vol. 53, no. 4, pp. 2664–2682, Apr. 1996.

[18] J. Zhang, W. Slysz, A. Verevkin, O. Okunev, G. Chulkova, A. Korneev, A. Lipatov, G. N. Goltsman, and R. Sobolewski, “Response time characterization of NbN superconducting single-photon detectors,” *IEEE Trans. Appl. Superconduct.*, vol. 13, no. 2, pp. 180–183, Jun. 2003.

[19] A. M. Kadin and M. W. Johnson, “Nonequilibrium photon-induced hotspot: A new mechanism for photodetection in ultrathin metallic films,” *Appl. Phys. Lett.*, vol. 69, no. 25, pp. 3938–3940, Dec. 1996.

[20] D. Saeedkia, A. H. Majedi, S. Safavi-Naeini, and R. R. Mansour, “Frequency and time-varying scattering parameters of a photo-excited superconducting microbridge,” *IEEE Microwave Wireless Compon. Lett.*, vol. 15, no. 8, pp. 510–512, Aug. 2005.

[21] K. Wiesenfeld, “Noisy precursors of nonlinear instabilities,” *J. Stat. Phys.*, vol. 38, p. 1071, 1985.

[22] Y. Kravtsov and E. Surovyatkina, “Nonlinear saturation of prebifurcation noise amplification,” *Phys.Lett. A*, vol. 319, p. 348, 2003.

[23] B. Abdo, E. Segev, O. Shtempluck, and E. Buks, “Intermodulation gain in nonlinear NbN superconducting microwave resonators,” *Appl. Phys. Lett.*, vol. 88, no. 1, p. 022508, Jan. 2006.

[24] C. C. Chin, D. E. Oates, G. Dresselhaus, and M. S. Dresselhaus, “Nonlinear electrodynamics of superconducting NbN and Nb thin films at microwave frequencies,” *Phys. Rev. B*, vol. 45, no. 9, pp. 4788–4798, Mar. 1992.

[25] R. Monaco, A. Andreone, and F. Palomba, “Intermodulation measurements in Nb superconducting microstrip resonators,” *J. Appl. Phys.*, vol. 88, no. 5, pp. 2898–2905, Sep. 2000.

[26] A. H. Majedi, S. K. Chaudhuri, and S. Safavi-Naeini, “Optical-microwave interaction modeling in high-temperature superconducting films,” *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 10, pp. 1873–1881, Oct. 2001.