Optical filtering by leaky guided modes in macroporous silicon

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(Received 17 February 2003; accepted 4 April 2003)

We propose an optical filtering mechanism in a porous material based on wavelength-dependent losses for leaky modes in pore waveguides. The spectral transmission characteristics of such filters can be controlled by applying thin-film coatings to the pore walls. Such filters will find application in the deep UV spectral range where traditional approaches to filter design fail due to lack of suitable materials. © 2003 American Institute of Physics. [DOI: 10.1063/1.1577382]

Macroporous silicon (MPSi) is an optical material produced by electroetching of a smooth silicon surface or a surface with pre-etched pits.1,2 Perfectly straight, more than 100 μm deep pores with diameters from hundreds of micrometers down to submicron scale have been successfully demonstrated.3 Application of MPSi as a two-dimensional photonic band gap material has been studied comprehensively.4–7 These studies assume light propagation mainly in the plane perpendicular to the pores. Also, it is supposed that silicon host is transparent, which restricts the wavelength range to the near infrared (λ>1100 nm).

Here we report a study of a type of optical filter based on light propagation in MPSi along the pore direction. The feasibility of using macroporous material as a short-pass filter has been recently demonstrated.5 It has been observed that light diffraction at a small aperture is wavelength dependent, which results in higher transmission for shorter wavelengths. A thin sheet of macroporous opaque material thus works as a short-pass optical filter. In this letter we consider long pores so that waveguiding in the pores becomes the key phenomenon that determines the light transmission. The waveguides, with cores formed by the pores, are essentially leaky as long as light can penetrate into a higher index cladding. The filtering is provided by the wavelength dependent optical losses. A similar filtering mechanism in the far infrared spectral range (λ>100 μm) has been reported for leaky waveguide arrays in narrow holes drilled in a metal sheet.9–11 Our experiments demonstrate that MPSi can serve as a short-pass filter in the UV spectral range. We predict that the transmission spectra can be effectively controlled through adjustment of the waveguide parameters. We expect that this approach to short-pass filter design can be extended to cover the deep UV range (λ~150 nm or even shorter). For shorter wavelengths, a similar filter based on meso-porous anodic alumina12,13 or electrochemically etched InP14 can be used. Development of optical elements, including filters, for the deep UV and extreme UV spectral range is considered to be a challenging problem, and we believe that our approach will become a substantial technological advance in this direction.

Optical filtering in long pores is mainly provided by wavelength dependent propagation losses. Using a simplified geometrical picture, a short-wavelength fundamental mode in a pore waveguide is presented by a ray trajectory with a shallow angle almost parallel to the pore walls, while a trajectory corresponding to long-wavelength mode would make a larger angle with respect to the pore walls. This causes more reflection events per unit of length as well as a smaller reflection, which results in higher optical losses for longer wavelengths. Also, if the waveguide structure is not perfectly symmetrical, there should be a cutoff wavelength above which the waveguiding is impossible.

This explanation can be supported by an estimation of losses in a waveguide formed by metallic-like boundaries surrounding a dielectric core (e.g., vacuum). We can use this approach at short wavelengths (λ<294 nm) where the optical properties of silicon resemble those of metals (κ>n, where κ and n are the imaginary and real parts of the refractive index, Fig. 1, left). An analytical solution is possible for a waveguide with flat boundaries. While it is not exactly the geometry of the pores, it gives a reasonable estimation of how the optical losses depend on the wavelength. For the Nth order (N=0,1,2,...) TE mode in a vacuum slab between the metal mirrors (κ>>n, κ>>1) separated by a distance d>>λ this estimation is15

\[ \alpha_{TE} = (N+1)^2 \frac{\lambda^2}{d^2} \frac{n}{n^2 + \kappa^2}. \]  

(1)

In the wavelength range λ>294 nm real part of the index is greater than the imaginary part, n>κ. Waveguiding in

![Image](https://example.com/image.png)

**FIG. 1.** Left: The optical constants of silicon (from Ref. 18) and the wavelength-dependent factor f(λ) for optical losses calculated using Eqs. (1) and (2). Right: Spectrum of optical losses in a vacuum slab between silicon walls calculated using exact numerical algorithm and estimated using Eqs. (1), (2), and (4).
the pores is still provided by the same mechanism, high reflection for a shallow incident angle. The difference with the metallic mirrors is in the electromagnetic field structure in the waveguide claddings. In the case of metallic claddings, the field is strongly decaying while in the high index dielectric cladding, the waveguide mode loses energy to waves propagating in the cladding, i.e., the waveguide becomes leaky. Due to the high absorption of silicon in this spectral range, the leaking waves are eventually absorbed in any case. Optical losses due to leakage only ($\kappa \ll n, d \gg \lambda$) are estimated as follows:\[16\]

$$\alpha_{\text{leakage}} \approx (N+1)^2 \frac{\ln^2 \left( \frac{1}{\sqrt{n^2-1}} \right)}{d^2}.$$  

(2)

Leaky modes have been studied in application to high power fiber transmission systems using hollow fibers in the midinfrared spectral region ($\text{CO}_2$ lasers).\(^{17}\)

Both Eqs. (1) and (2) predict similar dependence of optical losses on wavelength, waveguide thickness, and the mode order. Moreover, Eqs. (1) and (2) predict almost identical values of losses for $\lambda > 380 \text{ nm}$. Hence, Eq. (1) can be used over the entire spectrum for practical estimations. The transmission through the waveguide of length $L$ is proportional to an exponential factor such as $\exp(-\alpha L)$, which transfers a quadratic dependence of losses versus wavelength into a steep function with strong filtering of light with longer wavelengths. The macroporous material becomes a short-pass filter. However, at wavelengths $\lambda > 1100 \text{ nm}$ silicon is transparent, resulting in higher transmission for MPSi. To create a true short-pass filter (with cutoff in UV or deep UV), one must block the infrared transmission. In fact, as it is shown below, absorption in silicon becomes lower than the leakage losses at approximately $\lambda \approx 700–800 \text{ nm}$, which further restricts the applicability of the simple analysis developed in this letter.

For simplified practical estimations we note that for a particular material, silicon, the factors in Eqs. (1) and (2) depend on the optical indices and do not change considerably across the UV and visible spectrum. The index factor

$$f(\lambda) = \begin{cases} 
\frac{n(\lambda)^2 + \kappa(\lambda)^2}{\sqrt{n(\lambda)^2 - 1}} & \text{if } n(\lambda) < \kappa(\lambda) \\
1/\sqrt{n(\lambda)^2 - 1} & \text{if } n(\lambda) > \kappa(\lambda)
\end{cases}$$

(3)
calculated using published data for the optical constants of silicon\(^{18}\) is shown in Fig. 1. Note that Eqs. (1) and (2) are valid if $n \ll \kappa$ and $n \gg \kappa$, respectively, which may result in a discontinuity in Eq. (3) when $n = \kappa$. Function $f(\lambda)$ does not change much across the entire spectral range of interest (Fig. 1, left). Moreover, only the fundamental mode ($N = 0$) is essential because of the rapid increase of losses with $N$ increasing. As long as the excitation of odd modes in unlikely due to a vanishing overlapping integral of the incident flat wave and the modal field, the next mode after the fundamental is the mode with $N = 2$. Losses for this mode are almost one order of magnitude $([N+1]^2 = 9)$ higher. This reduces Eqs. (1) and (2) to a very simple and practical formula such as

$$\alpha = f_0 \lambda^2 / d^3.$$  

(4)

By comparing losses calculated using Eq. (4) (at the assumption of $f_0 \approx 0.09$) with exact numerical calculations for a slab waveguide, one can find that Eq. (4) gives surprisingly good ($\pm 10\%$ accuracy) estimation in $90–300 \text{ nm}$ wavelength range, despite of the fact that at the short wavelengths the condition $\kappa \gg 1$ is violated (Fig. 1, right). In the visible range, exact calculations give slightly higher losses. For wavelengths longer than $500 \text{ nm}$ Eq. (4) must be used with $f_0 = 0.28$. Absorption in silicon is also shown in Fig. 1 to emphasize the necessity of additional filtering at $\lambda > 800 \text{ nm}$. The simplified loss formula allows the determination of the filter’s cutoff wavelength (at $-3 \text{ dB}$ level) $\lambda_{-3 \text{ dB}}$ and the rejection wavelength (e.g., at $-20 \text{ dB}$ level)

$$\lambda_{-3 \text{ dB}} = \sqrt{\ln(10) \cdot \frac{d^2}{f_0 \cdot L} \cdot \ln(2)}, \quad \lambda_{-20 \text{ dB}} = \sqrt{\ln(100) \cdot \frac{d^2}{f_0 \cdot L}}.$$  

(5)

The ratio $\lambda_{-20 \text{ dB}} / \lambda_{-3 \text{ dB}}$ characterizing the sharpness of the filter becomes a constant $\sqrt{\ln(10)} / \ln(2) \approx 2.6$. Interestingly, the sharpness does not depend on the pore size and length. This sharpness might be acceptable for some applications: e.g., at $\lambda_{-3 \text{ dB}} = 150 \text{ nm}$, one gets $\lambda_{-20 \text{ dB}} = 390 \text{ nm}$, indicating that the visible spectrum is strongly suppressed. Sharper transmission characteristics, however, may be required for other challenging applications. Another interesting observation is that UV filters of this type do not necessarily require narrow size pores. Both the $3 \text{ dB}$ cutoff and $20 \text{ dB}$ rejection wavelengths are scaled proportionally to $d / d_{\text{TE}}$. This means that with deep enough pores, one can achieve short-wavelength operation of the filter even with relatively large pore diameter. For example, from Eq. (3), even at $d = 2 \mu \text{ m}$ one can get $\lambda_{-3 \text{ dB}} = 200 \text{ nm}$ (that is, one tenth of $d$) if pores with $L = 1.4 \text{ mm}$ are used. This, however, seems to be rather challenging from a technological point of view. Assuming that practically achievable aspect ratio is $d / L = 1/100$, the cutoff wavelength becomes $\lambda_{-3 \text{ dB}} = d_0 \sqrt{\ln(2) / \ln(100)} f_0 \approx 0.28d_0$.

The sharpness of the spectral transmission characteristics of a MPSi filter can be substantially improved by applying thin film coatings to the pore walls. This might be done by partial oxidization of MPSi, or by depositing a (multi)-layer coating inside the pores using chemical vapor deposition. The former approach is easier in realization, while the latter provides much more flexibility in controlling the pore waveguide transmission spectrum, thus deserving attention.

Figure 2, left, illustrates how a thin silica coating of the pore walls affects the optical transmission through a $50 \mu \text{ m}$
long structure. Here we present exact numerical calculations for a TE mode in a 1-μm-thick vacuum slab surrounded by silica films and then by a silicon host. The silica films work as antireflective (AR) coatings. For shallow incident angles, the minimal reflection of a film with thickness \( t \) and index \( n_{AR} \) is achieved at the wavelength \( \lambda_{AR} = 4t \sqrt{n_{AR}^{-1}} \), which agrees well with the calculated transmission dips in Fig. 2. Similarly, a multilayer high-reflection (HR) coating may increase transmission in a certain wavelength range. Figure 2, right, shows how the 2:1 pairs of silica/silicon nitride coating modify the transmission spectrum. Both AR and HR coatings clearly can improve the sharpness of spectral characteristics of MPSi filters.

Overall efficiency of MPSi filters is also affected by the light coupling to the pore waveguides. A simple estimation can be done for the rectangular \((a \times b)\) cross-section pores. In the deep UV range, where optical constants of silicon are almost metallic, we can assume that the modal field has a sinusoidal profile

\[
E_{N,M}(x,y) = \sin((N + 1) \pi x/a) \sin((M + 1) \pi y/b),
\]

where \( N, M = 0, 1, 2, 3... \) are the mode order indices. The beginning of the Cartesian coordinate system is placed at the corner of the rectangular pore. The squared overlapping integral of this field with plane incident wave becomes equal to

\[
I_{N,M} = \frac{64}{\pi^4} \left(\frac{1}{(N + 1)^2} \left(\frac{1}{(M + 1)^2}\right) \right)
\]

if \( N \) and \( M \) are even; 0 otherwise. (7)

Thus, in addition to the porosity factor determined as the relative area covered by pores, one has to apply an additional coupling factor for the fundamental mode equal to \( 64/\pi^4 = 0.66 \). High order modes have much smaller coupling: e.g., \( I_{2,0} = I_{0,2} = (1/9)I_{0,0} \); \( I_{4,0} = I_{0,4} = (1/25)I_{0,0} \); \( I_{2,2} = (1/81)I_{0,0} \); etc. They also experience stronger attenuation [see Eqs. (1) and (2)]. Total coupling to all the modes in a very wide pore supporting large number of modes equals 100% (if not counting the porosity factor) due to a mathematical identity

\[
\sum_{p=0}^{\infty} \sum_{q=0}^{\infty} \frac{1}{(2p + 1)^2} \frac{1}{(2q + 1)^2} = \frac{\pi^4}{64}.
\]

To confirm the filtering properties of MPSi, we have fabricated a set of samples with pore size of 3.5 μm (Fig. 3, left) and measured optical transmission in UV-visible range (Fig. 3, right). Technology used in the fabrication was electrochemical etching in hydrofluoric acid, initiated using periodic pits in a masking silica layer. More details on fabrication and some other aspects of the optical properties of such filters can be found elsewhere. Because of scattering, overall transmission measured by Perkin–Elmer spectrometer is very low. However, with the photodetector attached directly to the MPSi filter, 62% transmission for the wavelength of \( \lambda = 244 \) nm (second harmonic of an Ar⁺ ion laser line) has been measured (inset in Fig. 3, right). Oblique incidence of the laser beam resulted in smaller transmission. This must be attributed to lower excitation efficiency for the fundamental mode, while the higher order modes, even though excited by the oblique beam, show stronger losses.

In conclusion, we propose an optical filtering mechanism in a porous material based on wavelength-dependent losses for leaky modes in pore waveguides. Such filters will find application in the deep UV spectral range where traditional approaches to filter design fail due to lack of suitable materials.

The authors are greatful to Dr. Philip R. Swinehart for helpful discussions and suggestions, as long as for his help in editing the letter. They acknowledge the help of Yuri Danylyuk, Center for Smart Sensors and Integrated Microsystems, Wayne State University, in measuring the transmission spectra. They are grateful to Ralph Orban for his help in electrochemical etching, and Jeff Hardman for his help with reactive ion etching. They want to thank MDA for the support (Contract No. DASG60-02-P-0238).

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20. Lake Shore Cryotronics, Inc., Columbus, OH, patents pending.