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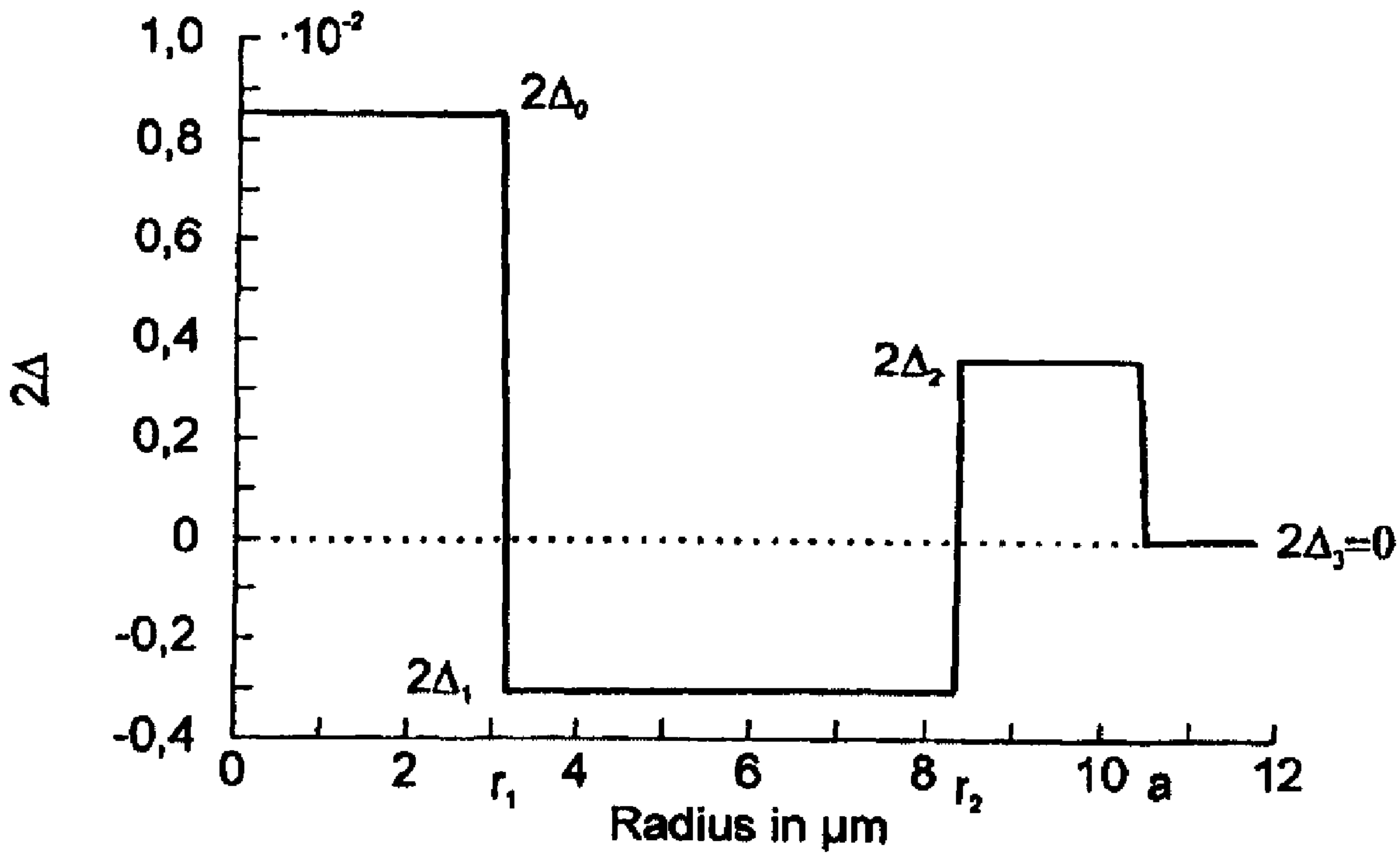
(54) Title: LOW DISPERSION SINGLEMODE OPTICAL FIBER WITH NON-CONSTANT INDEX PROFILE



(57) Abrégé/Abstract:
The invention relates to a single-mode low-dispersion optical fiber for wavelength division multiplexing (WDM) of an optical transmission link, comprising a central fiber core with a radius r_1, two inner layers of cladding with an outer radius r_2 or a, whereby a is greater than r_2, and an outer layer of cladding, whereby the refractive index n(r) of the fibers is inconstant as a function of the fibre radius r (a triple clad fiber). A fiber with a low dispersion in the wavelength range of approximately 1400 - 1700 nm, i.e. in the third optical window, can be manufactured using conventional production methods by selecting the appropriate profile and refractive index differentials between the core and or cladding without increasing the attenuation of said fibers. The transmission quality and output of an optical transmission link is increased by the inventive fibers in comparison with other standard optical fibers.

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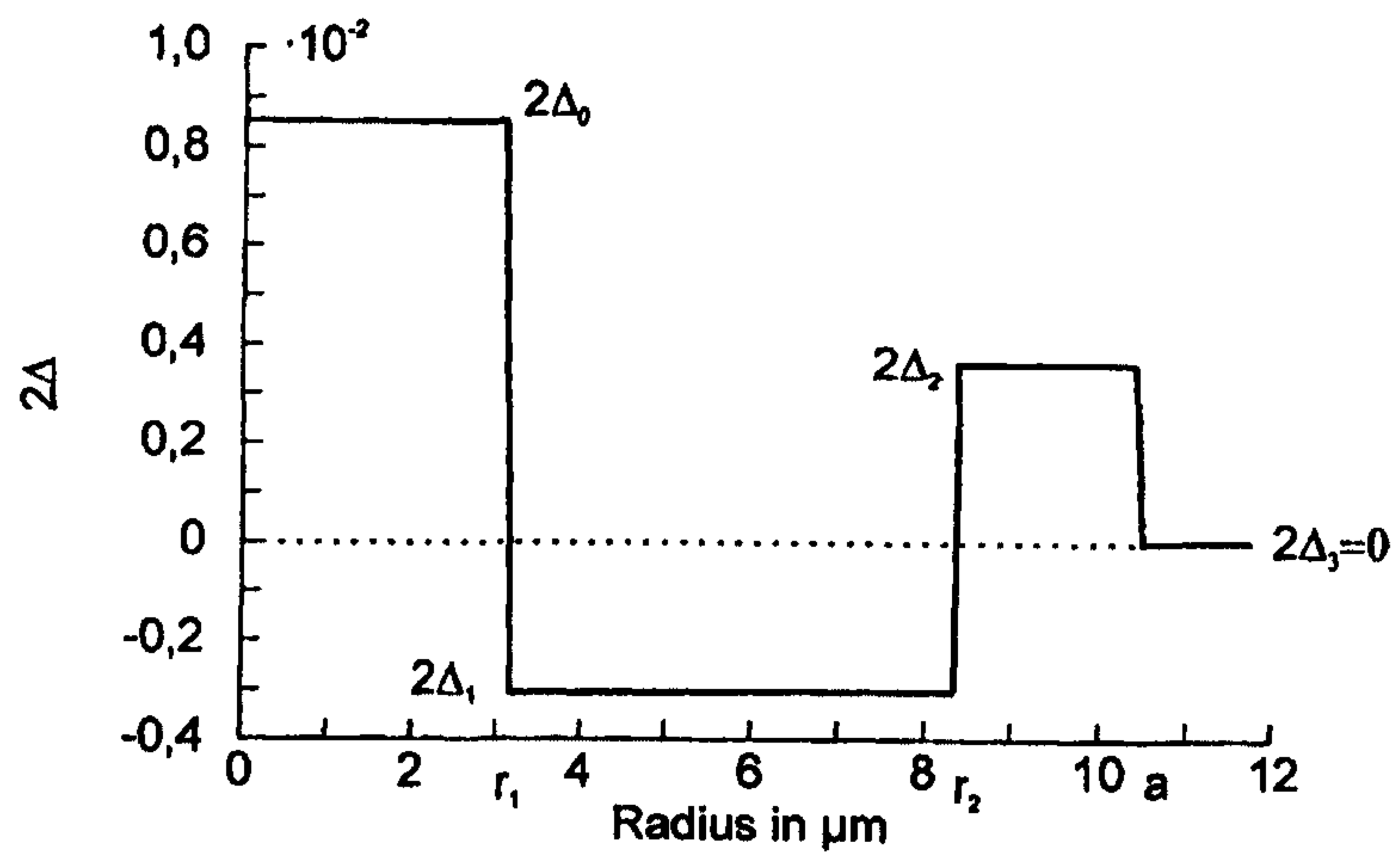
(57) Abstract

The invention relates to a single-mode low-dispersion optical fiber for wavelength division multiplexing (WDM) of an optical transmission link, comprising a central fiber core with a radius r_1, two inner layers of cladding with an outer radius r_2 or a, whereby a is greater than r_2, and an outer layer of cladding, whereby the refractive index n(r) of the fibers is inconstant as a function of the fibre radius r (a triple clad fiber). A fiber with a low dispersion in the wavelength range of approximately 1400 - 1700 nm, i.e. in the third optical window, can be manufactured using conventional production methods by selecting the appropriate profile and refractive index differentials between the core and or cladding without increasing the attenuation of said fibers. The transmission quality and output of an optical transmission link is increased by the inventive fibers in comparison with other standard optical fibers.



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Technical Field

The present invention relates to an optical single-mode fiber having low dispersion for the wavelength division multiplex operation (WDM) of optical transmission paths, which is made of a central fiber core, at least two inner fiber cladding layers, and of an outer fiber cladding layer (triple-clad fiber), the refractive index profile n(r) of the fiber not being constant as a function of the fiber radius r.

Background of the Invention

To be able to transmit ever greater data rates over single-mode fibers, the wavelength division multiplex method (WDM) is increasingly gaining in importance. In WDM operation of an optical transmission path, up to 80 to 100 channels having a spectral bandwidth of $\Delta\lambda$ are transmitted over one fiber. The number of channels that can be transmitted over one fiber of a given length is essentially limited by the fiber attenuation **[loss]** and dispersion at the wavelengths being used. Also, the channel spacing needed to ensure transmission quality means that the fibers must have a large enough spectral width for the transmission.

The fiberglass cables installed in the optical networks of telecommunications companies contain all-silica optical fibers, which are made of a fiber core and a fiber cladding. The minimum attenuation of all-silica fibers is within the third optical window, thus within the spectral region of around 1550 nm. In this wavelength range, powerful optical amplifiers are also available, e.g., erbium-doped fiber amplifiers (EDFA), which are used within the optical network to regenerate the transmission signals following a specific path **[line]** section. For these reasons, the WDM system currently used is conceived for the third optical window.

In the case of pre-installed glass fibers, one encounters the problem of dispersion. For normal standard fibers, the zero dispersion wavelength λ_0, at which no dispersion or only very slight dispersion of optical signals occurs, is $\lambda_0 \approx 1310$ nm. This means that a signal transmitted with a wavelength of about λ_0 is not or only slightly distorted, in particular, the pulse width is retained; however, the attenuation in this range is greater than in the third optical window. The chromatic dispersion $D(\lambda)$ in the case of standard fibers is substantially wavelength-dependent and, for $\lambda = 1550$ nm, amounts to about 16 to 17.5 ps/(km*nm). If an optical signal having wavelengths of about 1550 nm is transmitted, the pulse width is enlarged due to dispersion. This effect is an obstacle to a high transmission capacity; a chromatic dispersion of 16 to 17.5 ps/(km*nm) is much too high for ultra-high bit rate systems.

To be able, nevertheless, to use laid **[installed]** standard fibers in the third optical window, it is necessary to compensate for the dispersion, which entails considerable outlay. In this regard, one knows of dispersion-compensating fibers, for example, from U.S. Patent 5,568,583, which, at 1550 nm, exhibit a very high negative dispersion of D ≈ -100 ps/(km nm). These dispersion properties are achieved by raising the refractive index of the fiber core and by lowering the refractive index of a first cladding layer in comparison to the refractive index of the outer fiber cladding, made of silica. For the application, the dispersion-compensating fiber is spliced onto a standard fiber, so that the signal that is separated **[pulled apart]** by positive dispersion when propagating through the compensation fiber is compressed again **[reconstructed]** by the negative dispersion. A dispersion that is high in terms of absolute value is necessary to keep the length of the compensation fibers to a minimum.

It is also known to use special dispersion-shifted DS fibers, which have a zero dispersion wavelength of about 1550 nm, for the third optical window. A DS fiber of this kind is known, for example, from U.S. Patent 5,675,688. In principle, comparably to the dispersion-compensating fibers, the zero wavelengths are shifted through the use of a specific refractive index profile.

However, these DS fibers have decisive disadvantages when used in WDM operation. The dispersion curve $D(\lambda)$ does, in fact, intersect the wavelength axis at about λ_0 = 1550 nm, however, in comparison to the dispersion curve of standard fibers, it is merely shifted toward higher wavelength D values. Thus, near 1550 nm, it has a steep rise angle, i.e., a steep slope angle $S(\lambda_0)$, which lies at about 0.09ps/km*nm^2. This applies comparably to 1300 nm standard fibers, as well. This means, that for λ values, which differ from λ_0, one has to expect significant dispersion values, which rise virtually linearly with the spacing **[distance]** from λ_0. This is, of course, a serious disadvantage, which limits the usable WDM spectrum and, therefore, must be overcome. The second disadvantage of the DS fibers is the relatively small effective surface A_{eff} of the fibers, i.e., the small mode field diameter MFD **[in the core]** (Petermann II) and MFD_{eff}. They increase the nonlinear refractive index (Kerr coefficient) of the fibers and, thus, nonlinear effects (Brillouin und Raman scattering), which degrade the transmission quality.

Furthermore, to overcome the dispersion problem in the third optical window, optical monomode fibers have been developed as a replacement for standard fibers. In the relevant spectral region, the monomode fibers exhibit low chromatic dispersion, as well as low loss **[attenuation]**. From the company prospectus "TrueWave™ Single Mode Fiber" of AT&T Network Systems, a fiber is known, which, for wavelengths of about 1540 to 1560 nm, exhibits a chromatic dispersion D of $0.8 \leq D \leq 4.6$ps/(km*nm), given a mode field radius of 4.2 μm. Qualitatively, the refractive index profile n(r) shows a triangular core profile, the triangle resting on a broad platform, whose height makes up about one tenth of the height of the triangle. With respect to the silica glass value of n=1.4573 (outer cladding area), only positive n(r) values occur, if one assumes n=1.4573 as the zero level. One forgoes lowering the refractive index level, e.g., through incorporation of fluorine.

A dispersion-shifted fiber is also known from the EP

Patent 0851 251 245 A2. For wavelengths of around 1550 nm, it exhibits a dispersion of 1.0 to 4.5 ps/nm/km, a dispersion curve gradient of less than 0.13 $ps/nm^2/km$, and an effective surface of at least 70 μm^2. The core of the fiber is subdivided into four layers, each having a different refractive index level. Contiguous to this fiber core is the outer fiber cladding layer. Thus, it is a quadruple-clad fiber. Another quadruple-clad fiber having at least four levels with a flat dispersion curve (0.03 $ps/nm^2/km$) is known from WO 97/33188. To achieve the desired optical properties, the inner core level must be substantially increased in comparison to the reference refractive index of the outer clad level. In this context, close radius tolerances must be observed, in order to accommodate four layers. It is difficult to produce a refractive index profile with close radius tolerances on a regular basis, in the case where the profile varies considerably within the range of only a few micrometers. For the manufacturing, a plasma CVD process is suited. It enables fine layer structures of this kind to be precisely deposited. This process requires substantial outlay.

The usable spectrum in the third optical window is limited by the spectral operating range of the optical amplifiers (EDFA) used, which is between about 1510 and 1570 nm. However, since glass fibers, once installed, must be available for many years, one should anticipate future technical development and set the usable operating range of the fibers to be much higher, for instance between 1400 and 1700 nm.

From the EP 0 732 119 A1, a fiber is known, whose fiber core is partitioned into three or four layers, each having a different refractive index level, the maximum value of the refractive index deviation occurring within each layer being given by a reference value, and the dispersion within the wavelength range of 1400 to 1700 nm assuming values between -7 ps/(nm•km) and +5 ps/(nm•km).

Technical Objective

The object of the present invention is to make available a single-mode WDM fiber having a plurality of layers, each with a different refractive index level, for use in an ultra-high bit rate transmission system, which, given a fiber profile that is technologically simple and cost-effective to produce, has a usable operating range of preferably between 1400 and 1700 nm, a normally large, effective surface or mode-field radius, and a dispersion characteristic $D(\lambda)$, which, in the spectral region under consideration, is as flat as possible and assumes $D(\lambda)$ values having a maximum amount of 3.7 ps/(nm*km).

Detailed Description of the Invention

In accordance with this invention there is provided a single-mode optical fiber having low dispersion for the wavelength division multiplex operation (WDM) of an optical transmission path, made up of a central fiber core having a radius r_1, two inner fiber cladding layers having an outer radius r_2 and an outer radius a, respectively, where $a>r_2$, and an outer fiber cladding layer, the refractive index profile n(r) of the fiber not being constant as a function of the fiber radius r, and the outer fiber cladding layer, i.e., for the region r>a, having a relative refractive index profile

$\Delta(r)$, where $\Delta(r)=\frac{1}{2}\left(\frac{n(r)^2}{n_c^2}-1\right)$, for which it holds that $\Delta(r)\approx 0$, n_c being a constant reference refractive index; characterized in that for the radii r_1, r_2 and a, as well as for the relative refractive index profile $\Delta(r)$, where $\Delta(r)=\frac{1}{2}\left(\frac{n(r)^2}{n_c^2}-1\right)$ of the fiber, the following holds:

a) $8.0\ \mu m \le a \le 16\ \mu m$, $0.15 \le r_1/a \le 0.4$, and $0.65 \le r_2/a \le 0.85$,

b) in the fiber core, i.e., for $r \le r_1$, it holds that $\Delta_0 \ge \Delta(r) \ge 0$, where $3.5 \bullet 10^{-3} \le \Delta_0 \le 6.0 \bullet 10^{-3}$;

c) in the first inner fiber cladding layer, i.e., for $r_1 < r \le r_2$, it holds that $0 \ge \Delta(r) \ge \Delta_1$, where $-2.0 \bullet 10^{-3} \le \Delta_1 \le 0.6 \bullet 10^{-3}$;

d) in the second inner fiber cladding layer, i.e., for $r_2 < r \le a$, it holds that $\Delta_2 \ge \Delta(r) \ge 0$, where $1.0 \bullet 10^{-3} \le \Delta_2 \le 2{,}0 \bullet 10^{-3}$,

so that, within the wavelength range of between 1400 and 1700 nm, the fibers have a dispersion value of between -1.6 and +3,7 ps/(nm•km).

In this context, n_c is a constant reference refractive index, namely the refractive index of the outer cladding, which, as a rule, is made silica glass, where n_c =1.4573.

For small differences in refractive indices, as exist here, the relative refractive index defined by $\Delta(r)=\frac{1}{2}\left(\frac{n(r)^2}{n_c^2}-1\right)$ indicates approximately the absolute change in refractive index $n(r)-n_c$, in terms of the cladding refractive index, since $\Delta(r) \approx \frac{n(r) - n_c}{n_c}$.

The first inner cladding layer is directly contiguous to the fiber core and is surrounded by the second inner cladding layer. The sequence of layers terminates with the outer fiber cladding layer having reference refractive index n_c. Thus, in the simplest case, the fiber in accordance with the present invention is a triple-clad fiber.

The fiber core has a α profile ($\Delta(r) = \Delta_0(1-r^\alpha)$ where α=1...6) or a trapezoidal profile, or has a constant refractive index (rectangular profile). The refractive indices in the remaining layers are preferably constant. A triple-clad fiber of this kind can be produced simply and cost-effectively, using conventional manufacturing methods as well.

Radius r_1 is preferably between 2.5 μm and 5.5 μm, especially preferred is 3.5 $\mu m \leq r_1 \leq$ 4.5 μm. For radius r2, values of between 8 and 12 μm should be selected, preferably 9 $\mu m \leq r_2 \leq$ 11 μm. For radius a, it holds preferably that 9 $\mu m \leq a \leq$ 15 μm.

In another preferred embodiment of the present invention, it holds that: $-1.2\cdot10^{-3} \leq \Delta_1 \leq -0.6\cdot10^{-3}$.

A core profile form that is especially easy to implement, i.e., for $r < r_1$, is a rectangular profile. In this context, the absolute and relative core refractive index for $r < r_1$ is more or less constant, and, in the range of

$r \approx r_1$, it decreases to the value of the first inner cladding layer. Preferably, the three cladding layers likewise have a constant refractive index, which varies within the above indicated ranges.

In another especially preferred specific embodiment, the following parameters are selected for the fibers having a rectangular profile of the fiber core:

a) $3.7 \cdot 10^{-3} \leq \Delta_0 \leq 4.6 \cdot 10^{-3}$, preferably $\Delta_0 \approx 4.16 \cdot 10^{-3}$;

b) $-1.8 \cdot 10^{-3} \leq \Delta_1 \leq -1.4 \cdot 10^{-3}$, preferably $\Delta_1 \approx -1.59 \cdot 10^{-3}$;

c) $1.6 \cdot 10^{-3} \leq \Delta_2 \leq 1.9 \cdot 10^{-3}$, preferably $\Delta_2 \approx 1.75 \cdot 10^{-3}$;

d) $9.4\ \mu m \leq a \leq 11.4\ \mu m$, preferably $a \approx 10.4\ \mu m$, $0.15 \leq r_1/a \leq 0.4$, preferably $r_1/a \approx 0.3$, and $0.65 \leq r_2/a \leq 0.85$, preferably $r_2/a \approx 0.8$.

Another preferred form of the core profile is a triangular profile, $\Delta(r)$ assuming the maximum relative and, thus, also the absolute refractive index Δ_0 near the fiber midpoint and, up to $r \approx r_1$, decreasing linearly to the value of the first inner cladding layer. Contiguous thereto are, preferably, in turn, cladding layers having a constant refractive index of Δ_1, Δ_2 and, respectively, $\Delta_3 = 0$.

In another especially preferred specific embodiment, the following parameters are selected for fibers whose core has a triangular profile:

a) $4.7 \cdot 10^{-3} \leq \Delta_0 \leq 5.8 \cdot 10^{-3}$, preferably $\Delta_0 \approx 5.31 \cdot$

10^{-3};

b) $-1.0 \cdot 10^{-3} \le \Delta_1 \le -0.8 \cdot 10^{-3}$, preferably $\Delta_1 \approx -0.9 \cdot 10^{-3}$;

c) $1.1 \cdot 10^{-3} \le \Delta_2 \le 1.4 \cdot 10^{-3}$, preferably $\Delta_2 \approx 1.25 \cdot 10^{-3}$;

d) $12.9\ \mu m \le a \le 14.9\ \mu m$, preferably $a \approx 13.9\ \mu m$, $0.15 \le r_1/a \le 0.4$, preferably $r_1/a \approx 0.3$, and $0.65 \le r_2/a \le 0.85$, preferably $r_2/a \approx 0.8$.

Another preferred form of the core profile is a parabola profile of the relative or of the absolute refractive index, the maximum relative and, thus, also absolute refractive index Δ_0 being assumed in the vicinity **[near]** the fiber midpoint, and $\Delta(r)$ up to $r \approx r_1$ decreasing more or less parabolically to the value of the first inner cladding layer. Preferably contiguous thereto, in turn, are cladding layers having a constant refractive index Δ_1, Δ_2 or 0. Fewer mechanical tensions result when there is a continuous **[stepless]** transition of refractive indices into one another. For that reason, under certain conditions, a parabola profile of the fiber core is more stable than a rectangular profile.

In another especially preferred specific embodiment, the following parameters are selected for the fibers where the fiber core has a parabola profile:

a) $3.9 \cdot 10^{-3} \le \Delta_0 \le 4.8 \cdot 10^{-3}$, preferably $\Delta_0 \approx 4.34 \cdot 10^{-3}$;

b) $-1.1 \cdot 10^{-3} \le \Delta_1 \le -0.9 \cdot 10^{-3}$, preferably $\Delta_1 \approx -1.03 \cdot 10^{-3}$;

c) $1.3 \cdot 10^{-3} \le \Delta_2 \le 1.7 \cdot 10^{-3}$, preferably $\Delta_2 \approx 1.5 \cdot 10^{-3}$;

d) $12.0\ \mu m \le a \le 14.0\ \mu m$, preferably $a \approx 13.0\ \mu m$, $0.15 \le r_1/a \le 0.4$, preferably $r_1/a \approx 0.3$, and $0.65 \le r_2/a \le 0.85$, preferably $r_2/a \approx 0.8$.

The profile specifications must be understood as theoretical setpoint entries. In practice, drastic jumps **[sharp discontinuities]** in the refractive index are not able, as a rule, to be precisely implemented; rather all corners of a theoretical profile are rounded off. The refractive index characteristics are produced by depositing thin layers, so that, in practice, even a theoretically constant n(r) has a wave-shaped **[undulating]** characteristic. Therefore, the above explanations refer to the target specifications. Moreover, at r = 0, for example, a theoretically rectangular core profile often has a so-called middle dip, a decline in the refractive index and, therefore, merely a refractive index characteristic that can be approximated by a rectangle. However, the middle dip is able to be avoided through improved technology in the manufacturing process.

The described profiles are able to be produced using conventional modified chemical vapor deposition (MCVD) techniques.

The fiber in accordance with the present invention has a chromatic dispersion D, which, for wavelengths from 1400 nm to 1700 nm lies within the range of between -1.6 to 3.7 ps/(nm km) and, thus, substantially below the value of standard all-silica fibers. Given a careful manufacturing of the fibers, the simple structures and relatively large field radii also ensure small **[low]** polarization mode dispersion (PMD) values of less than 0.5 $ps/km^{1/2}$.

The fibers are preferably made for the most part of silica glass, which is doped with appropriate materials, preferably with germanium or fluorine, in order to raise or lower the refractive index in the core and in the cladding layers. Since the core doping required to reach the differences in refractive indices varies within the usual range, one should not expect the attenuation values of the WDM fibers to be higher than the current standard.

In addition, the core radii and, in particular, the effective radii w_{eff} of the fibers in accordance with the present invention are comparable to corresponding values of standard fibers. Since these quantities determine the polarization mode dispersion and the quantity of non-linear effects, both the PMD as well as the non-linear Kerr coefficient are comparable to those of standard fibers.

When fibers in accordance with the present invention are used, the transmission quality and transmission power of an optical transmission route are able to be enhanced as compared to standard optical fibers. Moreover, since a stabler signal form results from the lower dispersion, the glass fiber distance between the transmitter and receiver, respectively amplifier station, can be lengthened, which represents a cost savings. The small amount of pulse broadening makes it possible for substantially higher data rates to be transmitted, which is a prerequisite for ultra-high bit rate transmission systems.

Brief description of the drawing, whose figures show:

Figure 1 a refractive index profile $\Delta(r)$ having a rectangular core structure;

Figure 2 the dispersion and the field radii w_n, w_f and

w_{eff} as a function of the wavelength for the profile from Figure 1;

Figure 3 a refractive index profile $\Delta(r)$ having a parabolic core structure;

Figure 4 the dispersion and the field radii w_n, w_f and w_{eff} as a function of the wavelength for the profile from Figure 3;

Figure 5 a refractive index profile $\Delta(r)$ having a triangular core structure;

Figure 6 the dispersion and the field radii w_n, w_f and w_{eff} as a function of the wavelength for the profile from Figure 5.

Preferred Specific Embodiments

In Figures 1,3 and 5, three fiber profiles $\Delta(r)$ are depicted, the relative refractive index $\Delta(r) = \frac{1}{2}\left(\frac{n(r)^2}{n_c^2} - 1\right)$ being plotted as a function of fiber radius r. The fibers constructed in this manner have the following dispersion values D and are, thus, ideal, extremely broadband WDM fibers for the WDM operation in the third optical window: $D(\lambda) \leq 3.3$ ps/km*nm (profile 1, Figure 1), $D(\lambda) \leq 2.8$ ps/km*nm (profile 2, Figure 3) and $D(\lambda) \leq 3.1$ ps/km*nm (profile 3, Figure 5) in the spectral region $1450 \leq \lambda \leq 1650$ nm.

Due to their relatively simple structure (rectangular, parabolic, triangular core region, otherwise stepped **[There is a step-index fiber, but I'm not sure if this is meant here. The German text simply says "steps"]**), the described profiles can be conveniently manufactured using conventional MCVD techniques. Given a careful fiber fabrication, the simple structures and the large mode field radii ensure low PMD values ($<0.5 ps/km^{1/2}$).

Figure 1 shows an example of a fiber profile in accordance with the present invention. The relative level is $2\Delta=0$, thus, $n=n_c$ (refractive index of the outer cladding region). The relative level is shown as a dotted line. Profile 1 is a triple-clad profile having the rectangular profile of the fiber core having the following characteristic data:

$2\Delta_0=8.36\cdot10^{-3}$ (fiber core)

$2\Delta_1=-3.18\cdot10^{-3}$ (first inner cladding layer)

$2\Delta_2=3.5\cdot10^{-3}$ (second inner cladding layer)

$2\Delta_3=0$ (per definition, outer cladding layer)

Radii, respectively radii proportions $a = 10.4\mu m$, $r_1/a=0.3$ and $r_2/a=0.8$.

The fibers are manufactured, for example, on a silica glass base, for example, where $n_c = 1.4573$. In this case, the mentioned relative refractive indices Δ_i correspond to the following real refractive indices:

$n_0=1.4634$ (fiber core)

$n_1=1.4550$ (first inner cladding layer)

$n_2=1.4599$ (second inner cladding layer)

$n_c=1.4573$ (outer cladding layer)

Starting out from silica glass as a base material, the refractive indices can be changed by doping with germanium or fluorine. The doping concentrations of the implantations required for this, in particular of the germanium, are so low, in this context, that there is no significant increase in the fiber attenuation, as is observed, for example, in the case of dispersion-compensating fibers. In addition, in the case of the fiber doping, one can avoid the difficulties that arise when working with high fluorine concentrations.

The critical wavelength λ_c was calculated and amounts to λ_c=1216 nm.

Figure 2a shows the characteristic spectral curve of chromatic dispersion $D(\lambda)$; and Figure 2b depicts the spectral mode field radius curves w_n (Petermann I), w_f (Petermann II) and w_{eff} for profile 1. The values were computed from the profile data in a simulation calculation.

At wavelengths of around 1400 nm, dispersion $D(\lambda)$ is barely within the negative range. It rises to values of maximally 3.6 ps/km*nm, which are reached at wavelengths of around 1700 nm. Between λ=1550 and 1650 nm, the dispersion is positive (abnormal), and it increases from 2.8 to 3.4 ps/km*nm, so that, in this range, the dispersion curve shows a small slope $\Delta D/\Delta\lambda$.

In the entire described spectral range, the mode field radii are between 3.5 and 5 μm (w_f and w_{eff}) and, respectively, between 4 and 7 μm (w_n), thus within the range of standard fibers, where $w_{eff} \approx 4.5$ μm.

Figure 3 shows the profile of another triple-clad fiber according to the present invention, having the parabola profile of the fiber core. The characteristic data of the fibers are:

$2\Delta_0=8.68\cdot10^{-3}$ (maximum refractive index in the fiber core, the actual profile characteristic $\Delta(r)$, at this value, is only at r=0, and then drops off)

$2\Delta_1=-2.06\cdot10^{-3}$

$2\Delta_2=3.0\cdot10^{-3}$

Radii(ratios) $a=13.0\mu m$, $r_1/a=0.3$ and $r_2/a=0.8$.

The critical wavelength of these fibers amounts to $\lambda_c=1482$ nm.

Figure 4a, in turn, shows the spectral characteristic of the chromatic dispersion $D(\lambda)$, and Figure 4b illustrates the spectral mode-field radius curves w_f, w_n and w_{eff}. Between 1450 and 1650 nm, the dispersion is positive and remains below 3ps/km*nm.

Figure 5 depicts the profile of another triple-clad fiber according to the present invention whose fiber core has a triangular profile. The characteristic data of the fibers are:

$2\Delta_0(max)=10.62\cdot10^{-3}$ (maximum refractive index in the fiber core)

$2\Delta_1=-1.81\cdot10^{-3}$,

$2\Delta_2=2.5\cdot10^{-3}$,

Radii(ratios) $a=13.9\mu m$, $r_1/a=0.3$ and $r_2/a=0.8$. The critical wavelength is $\lambda_c=1482$ nm.

Figure 6 shows the spectral characteristic of the chromatic dispersion and the spectral mode-field radius curves. Between 1450 and 1650 nm, in turn, the dispersion is positive and, given a small a slope angle, remains below 3.1ps/km*nm.

A tolerance analysis was performed on the described profiles and the indicated parameters, in which the relative refractive indices Δ_i and radius a were each altered by ±1%. For values r_i/a, an absolute change of around ±0.005 was assumed. In response to a single parameter change, the critical wavelength changes by maximally about 15 nm, the greatest deviation occurring in response to a change of core radius a. With respect to the dispersion characteristic, the parameter changes lead to a deviation of maximally ±2 ps/km*nm, which likewise leads to permissible dispersion values. Field radius w_n changes by maximally ±0.5 μm, while field radii w_{eff} and w_f are substantially stabile.

Overall, therefore, one can assess that the responsivity to parameter changes is able to be controlled by technology. Since in the case of the fibers according to the present invention, the waveguide dispersion enters into the dispersion behavior, a somewhat greater responsivity to parameters is to be expected than in the case of standard fibers at 1300 nm. However, these responsivity levels are far below those of dispersion-compensation fibers which, for their part, are able to be routinely fabricated.

Industrial Applicability

The fibers in accordance with the present invention are advantageously suited for optical data transmission in the third optical window and, thus, for high bit-rate optical communications networks to be newly established. Due to the substantially reduced dispersion as compared to standard fibers, the fiber in accordance with the present invention is specially suited for wavelength division multiplex operation, high transmission rates with high transmission quality being attainable.

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CLAIMS:

1. A single-mode optical fiber having low dispersion for the wavelength division multiplex operation (WDM) of an optical transmission path, made up of a central fiber core having a radius r_1, two inner fiber cladding layers having an outer radius r_2 and an outer radius a, respectively, where $a>r_2$, and an outer fiber cladding layer, the refractive index profile n(r) of the fiber not being constant as a function of the fiber radius r, and the outer fiber cladding layer, i.e., for the region r>a, having a relative refractive index profile $\Delta(r)$, where

$\Delta(r)=\frac{1}{2}\left(\frac{n(r)^2}{n_c^2}-1\right)$, for which it holds that $\Delta(r)\approx 0$, n_c being a constant reference refractive index;

characterized in that

for the radii r_1, r_2 and a, as well as for the relative refractive index profile $\Delta(r)$, where $\Delta(r)=\frac{1}{2}\left(\frac{n(r)^2}{n_c^2}-1\right)$ of the fiber, the following holds:

a) $8.0\ \mu m \le a \le 16\ \mu m$, $0.15 \le r_1/a \le 0.4$, and $0.65 \le r_2/a \le 0.85$,

b) in the fiber core, i.e., for $r \le r_1$, it holds that $\Delta_0 \ge \Delta(r) \ge 0$, where $3.5\cdot 10^{-3} \le \Delta_0 \le 6.0\cdot 10^{-3}$;

c) in the first inner fiber cladding layer, i.e., for $r_1 < r \le r_2$, it holds that $0 \ge \Delta(r) \ge \Delta_1$, where $-2.0\cdot 10^{-3} \le \Delta_1 \le 0.6\cdot 10^{-3}$;

d) in the second inner fiber cladding layer, i.e., for $r_2 < r \le a$, it holds that $\Delta_2 \ge \Delta(r) \ge 0$, where $1.0\cdot 10^{-3} \le \Delta_2 \le 2,0\cdot 10^{-3}$,

so that, within a wavelength range of between 1400 and 1700 nm, the fiber has a dispersion value of between

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-1.6 and +3,7 ps/(nm·km).

2. The optical fiber as recited in claim 1, characterized in that, for radius r_1, it holds that:

$2.5\ \mu m \leq r_1 \leq 5.5\ \mu m$.

3. The optical fiber as recited in claim 1, characterized in that, for radius r_1, it holds that:

$3.5\ \mu m \leq r_1 \leq 4.5\ \mu m$.

4. The optical fiber as recited in claim 1, characterized in that, for radius r_2, it holds that:

$8\ \mu m \leq r_2 \leq 12\ \mu m$.

5. The optical fiber as recited in claim 1, characterized in that, for radius r_2, it holds that:

$9\ \mu m \leq r_2 \leq 11\ \mu m$.

6. The optical fiber as recited in claim 1, characterized in that, for the radius a, it holds that:

$9\ \mu m \leq a \leq 15\ \mu m$.

7. The optical fiber as recited in claim 1 or 6, characterized in that, the value Δ_i varies within the following limits:

$-1.2 \cdot 10^{-3} \leq \Delta_1 \leq -0.6 \cdot 10^{-3}$.

8. The optical fiber as recited in claim 1, 6 or 7, characterized in that in the region of the fiber core, the refractive index profile has a rectangular, triangular, trapezoidal, or parabola-like shape, $\Delta(r)$ assuming the maximum relative value Δ_0, at least in the vicinity of the fiber midpoint for $r \approx 0$.

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9. The optical fiber as recited in claim 1 or 7, characterized in that in the region of the fiber core, the refractive index profile is rectangular, in which case it holds that:

a) $3.7\cdot10^{-3} \leq \Delta_0 \leq 4.6\cdot10^{-3}$;

b) $-1.8\cdot10^{-3} \leq \Delta_1 \leq -1.4\cdot10^{-3}$;

c) $1.6\cdot10^{-3} \leq \Delta_2 \leq 1.9\cdot10^{-3}$;

d) $9.4\ \mu m \leq a \leq 11.4\ \mu m$, $0.15 \leq r_1/a \leq 0.4$, and $0.65 \leq r_2/a \leq 0.85$.

10. The optical fiber as recited in claim 1 or 7, characterized in that in the region of the fiber core, the refractive index profile is rectangular, in which case it holds that:

a) $\Delta_0 \approx 4.16\cdot10^{-3}$;

b) $\Delta_1 \approx -1.59\cdot10^{-3}$;

c) $\Delta_2 \approx 1.75\cdot10^{-3}$;

d) $a \approx 10.4\ \mu m$, $r_1/a \approx 0.3$, and $r_2/a \approx 0.8$.

11. The optical fiber as recited in claim 1 or 7, characterized in that, in the region of the fiber core, the refractive index profile is triangular, in which case it holds that:

a) $4.7\cdot10^{-3} \leq \Delta_0 \leq 5.8\cdot10^{-3}$;

b) $-1.0\cdot10^{-3} \leq \Delta_1 \leq -0.8\cdot10^{-3}$;

c) $1.1\cdot10^{-3} \leq \Delta_2 \leq 1.4\cdot10^{-3}$;

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d) 12.9 μm ≤ a ≤ 14.9 μm, 0.15 ≤ r_1/a ≤ 0.4, and 0.65 ≤ r_2/a ≤ 0.85.

12. The optical fiber as recited in claim 1 or 7, characterized in that, in the region of the fiber core, the refractive index profile is triangular, in which case it holds that:

a) $\Delta_0 \approx 5.31 \cdot 10^{-3}$;

b) $\Delta_1 \approx -0.9 \cdot 10^{-3}$;

c) $\Delta_2 \approx 1.25 \cdot 10^{-3}$;

d) a ≈ 13.9 μm, $r_1/a \approx 0.3$, and $r_2/a \approx 0.8$.

13. The optical fiber as recited in claim 1 or 7, characterized in that, in the region of the fiber core, the refractive index has a parabola profile, in which case it holds that:

a) $3.9 \cdot 10^{-3} \le \Delta_0 \le 4.8 \cdot 10^{-3}$;

b) $-1.1 \cdot 10^{-3} \le \Delta_1 \le -0.9 \cdot 10^{-3}$;

c) $1.3 \cdot 10^{-3} \le \Delta_2 \le 1.7 \cdot 10^{-3}$;

d) 12.0 μm ≤ a ≤ 14.0 μm, 0.15 ≤ r_1/a ≤ 0.4, and 0.65 ≤ r_2/a ≤ 0.85.

14. The optical fiber as recited in claim 1 or 7, characterized in that, in the region of the fiber core, the refractive index has a parabola profile, in which case it holds that:

a) $\Delta_0 \approx 4.34 \cdot 10^{-3}$;

b) $\Delta_1 \approx -1.03 \cdot 10^{-3}$;

c) $\Delta_2 \approx 1.5 \cdot 10^{-3}$;

d) $a \approx 13.0\ \mu m$, $r_1/a \approx 0.3$, and $r_2/a \approx 0.8$.

15. The optical fiber as recited in claim 1 or 7, characterized in that, in the region of the inner fiber cladding layers, the relative refractive index $\Delta(r)$ is constant and amounts to about Δ_1 and about Δ_2, respectively.

16. The optical fiber as recited in claim 1 or 7, characterized in that the fibers are made for the most part of silica glass, which is doped with appropriate materials for modifying the refractive indices, in order to raise or lower the refractive index in the core and in the cladding layers.

17. The optical fiber as recited in claim 1 or 7, characterized in that the fibers are made for the most part of silica glass, which is doped with germanium or fluorine, in order to raise or lower the refractive index in the core and in the cladding layers.

18. The optical fiber as recited in any one of claims 1 to 17, characterized in that in the wavelength range of about 1400 to about 1700 nm, it exhibits a dispersion of less than 4 ps/(km nm).

19. The optical fiber as recited in any one of claims 1 to 17, characterized in that in the wavelength range of about 1400 to about 1700 nm, it exhibits a dispersion of about 3 ps/(km nm).

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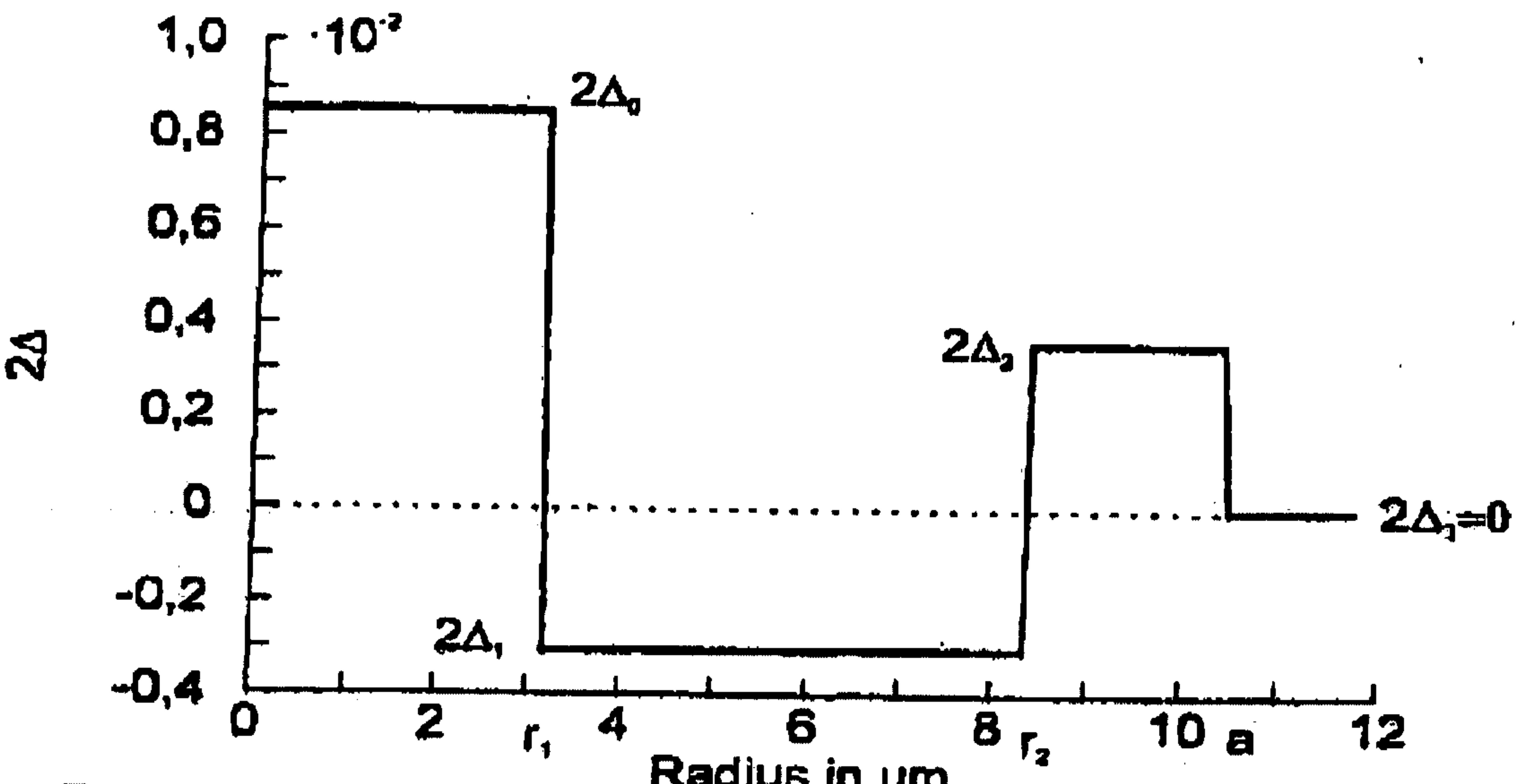
PATENT AGENTS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2Δ
2Δ0
2Δ1
2Δ2
2Δi=0
0
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r1
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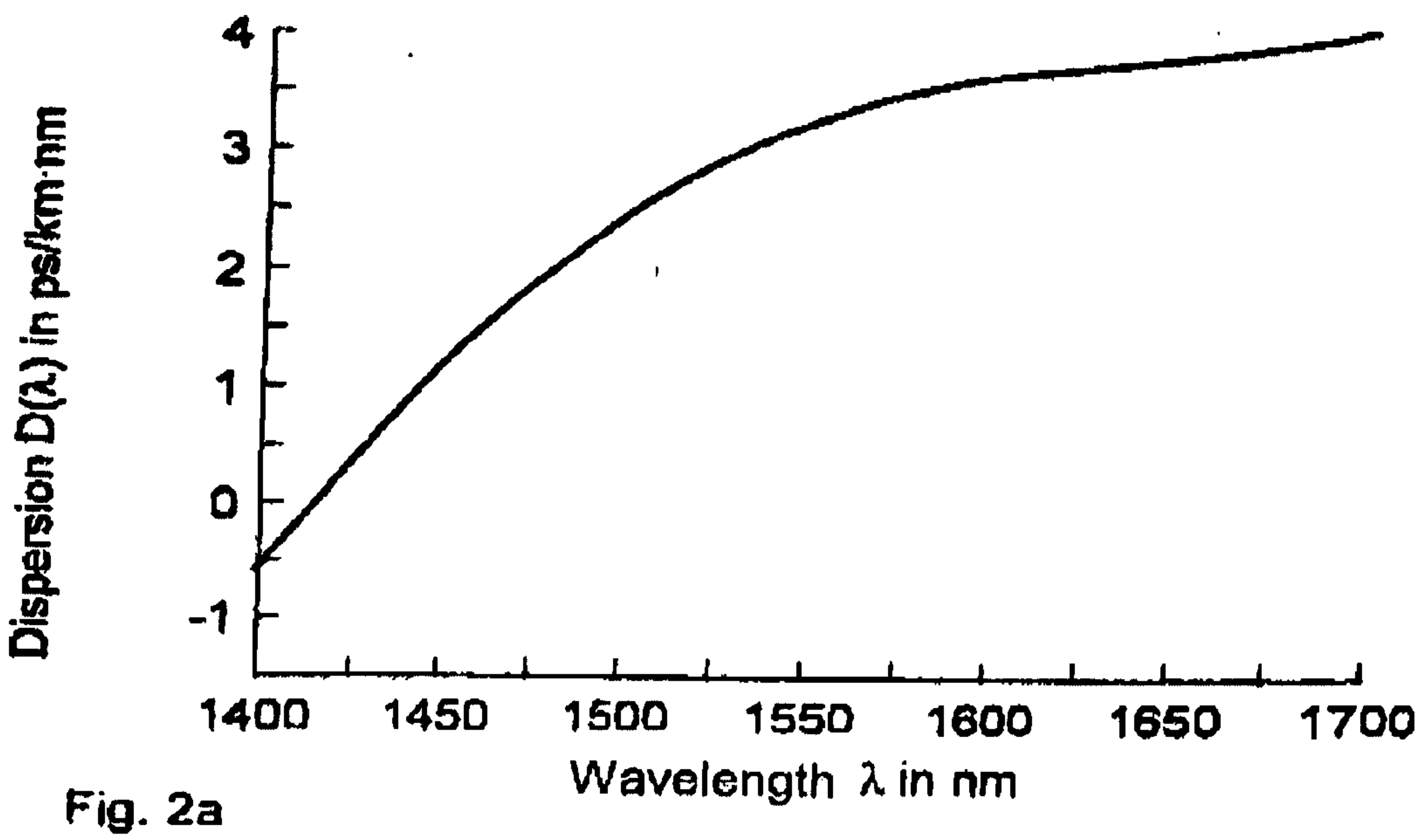
6
8
r2
10
a
12
Radius in µm

Fig. 1


Dispersion D(λ) in ps/km·nm
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-1
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1500
1550
1600
1650
1700
Wavelength λ in nm

Fig. 2a

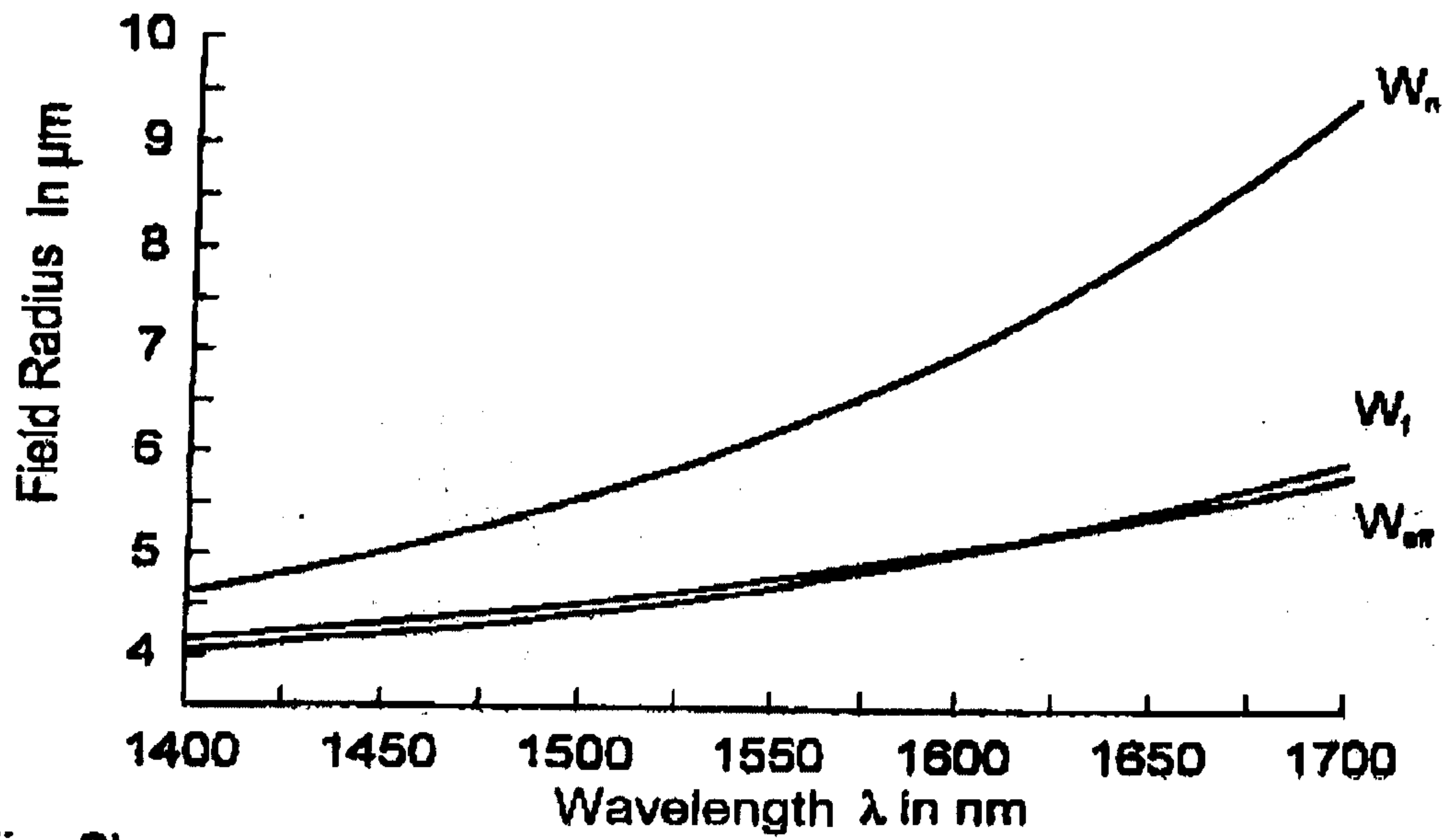
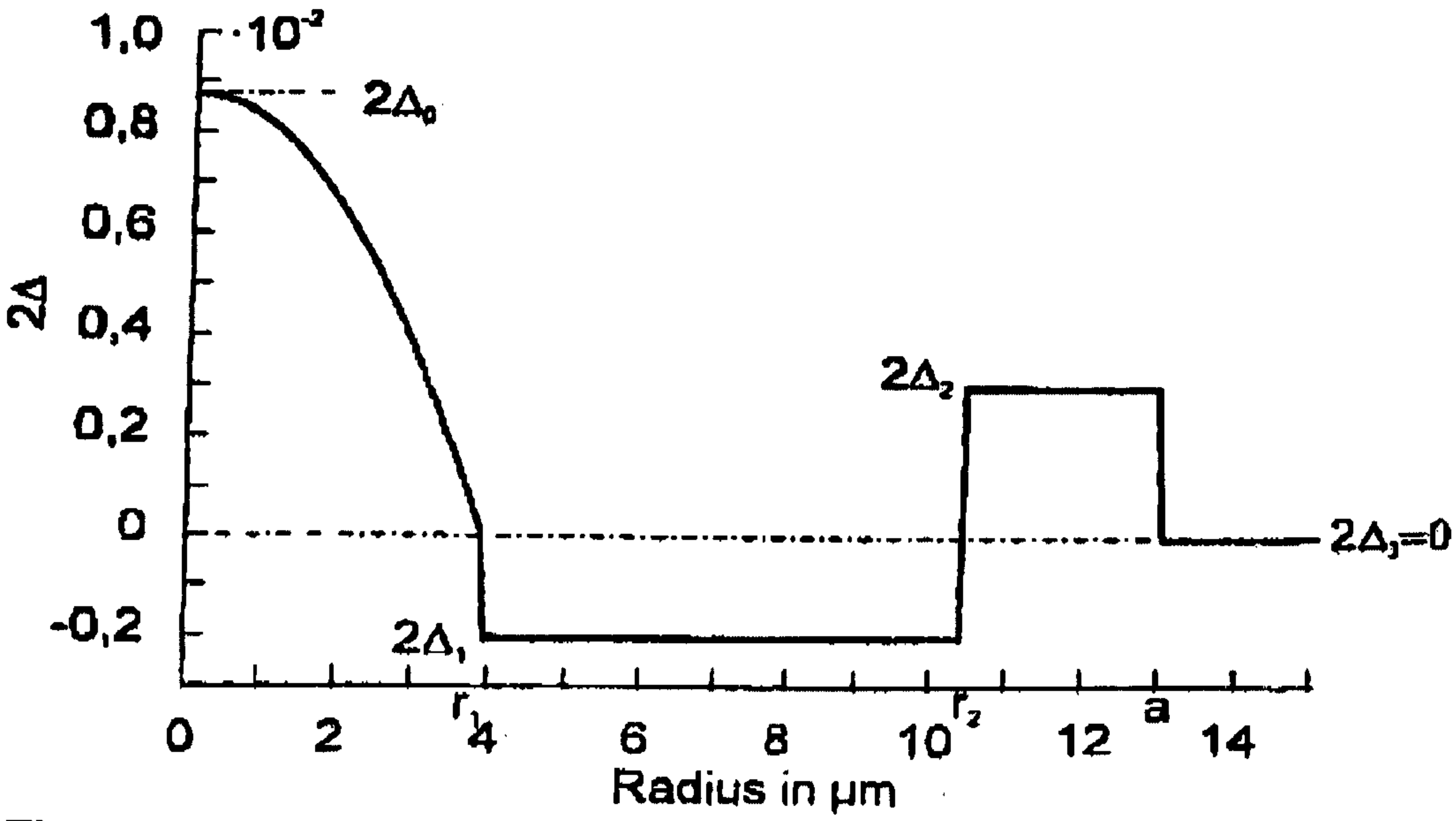

10
9
8
7
6
5
4
Field Radius in µm
W_n
W_t
W_{eff}
1400
1450
1500
1550
1600
1650
1700
Wavelength λ in nm

Fig. 2b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2Δ
$2\Delta_0$
$2\Delta_1$
$2\Delta_2$
$2\Delta_3=0$
0
2
r_1
4
6
8
10
r_2
12
a
14
Radius in µm

Fig. 3

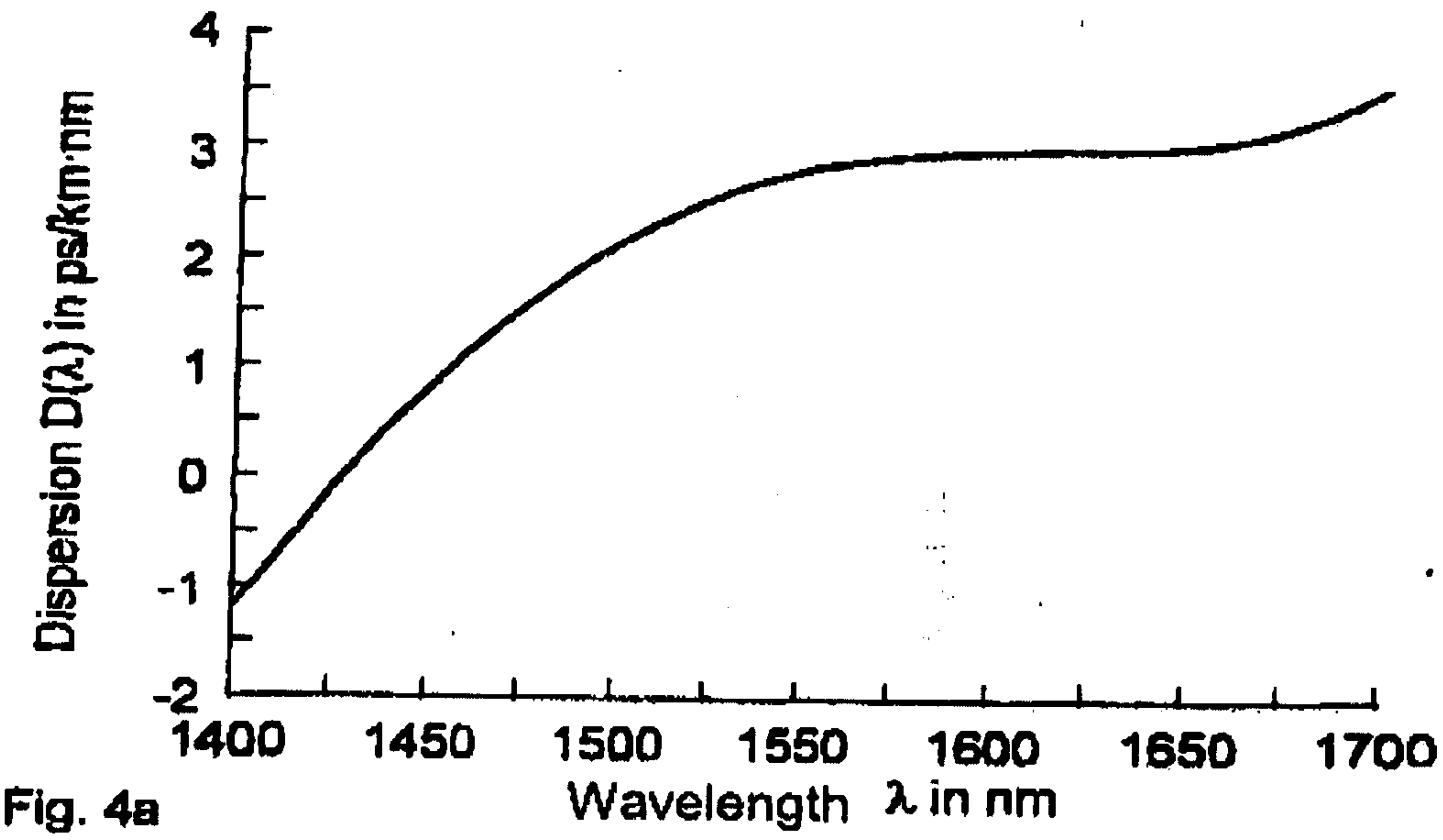

4
3
2
1
0
-1
-2
Dispersion D(λ) in ps/km·nm
1400
1450
1500
1550
1600
1650
1700
Wavelength λ in nm

Fig. 4a

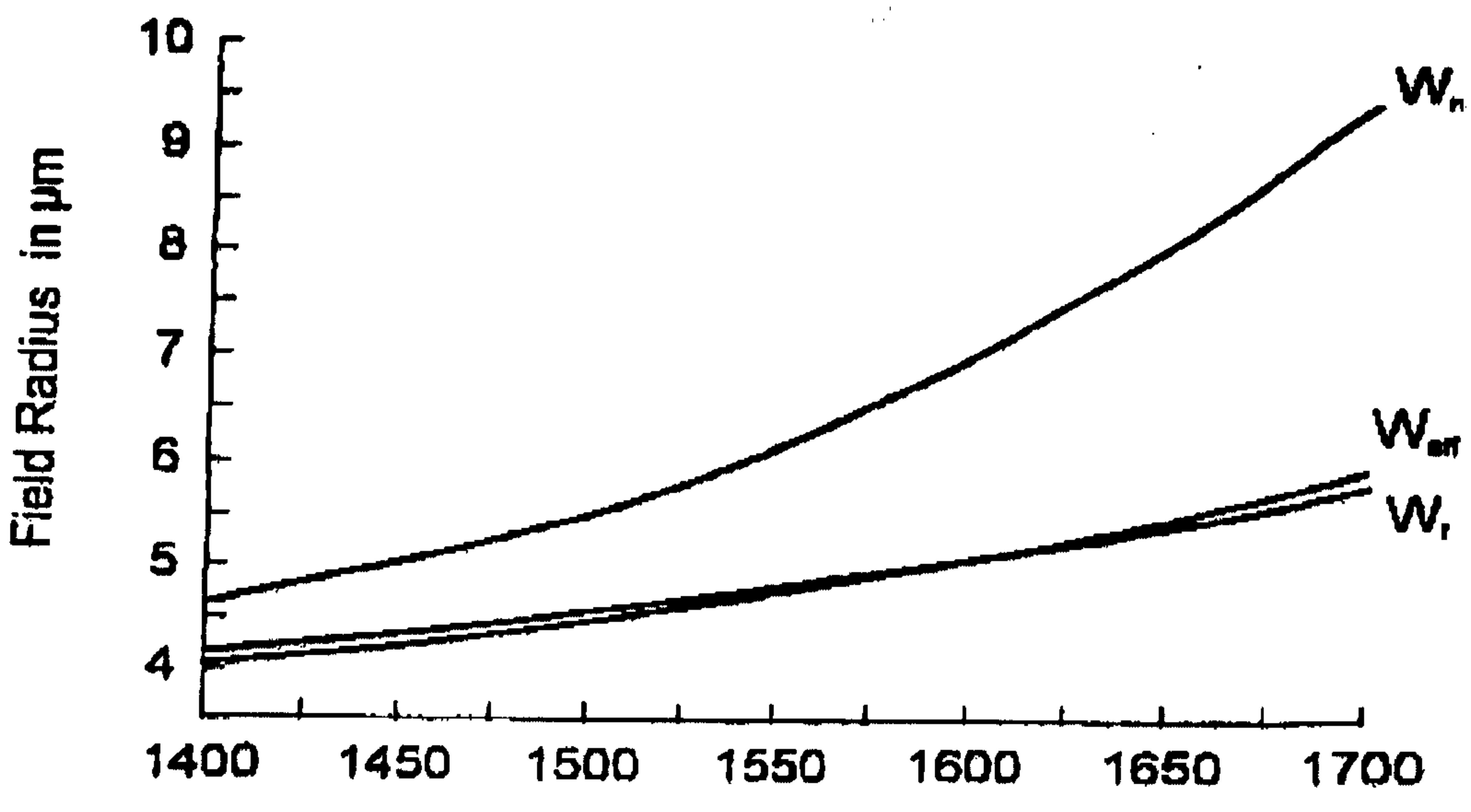
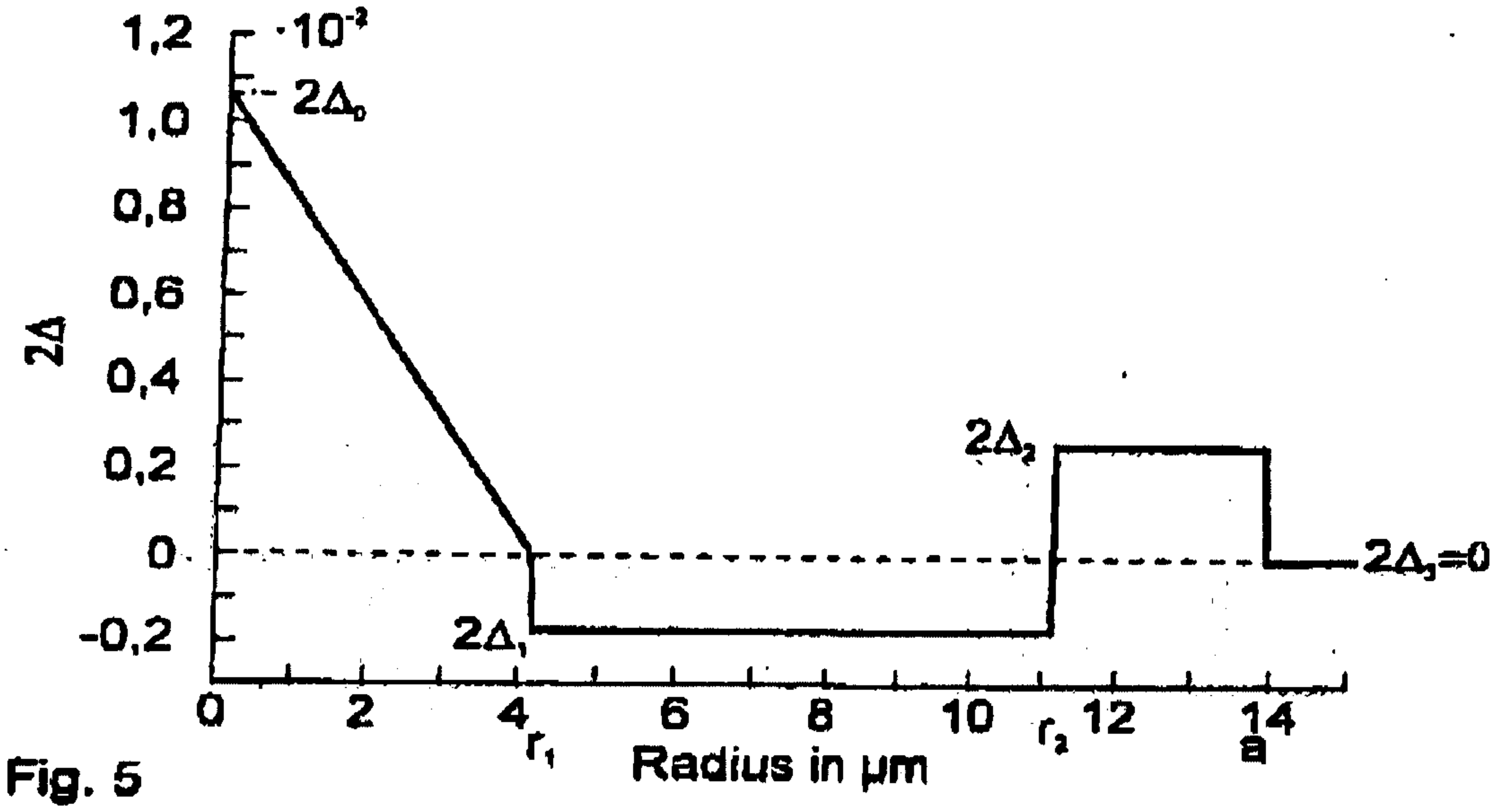

10
9
8
7
6
5
4
Field Radius in µm
W_n
W_{eff}
W_r
1400
1450
1500
1550
1600
1650
1700
Wavelength λ in nm

Fig. 4b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2Δ
0,4
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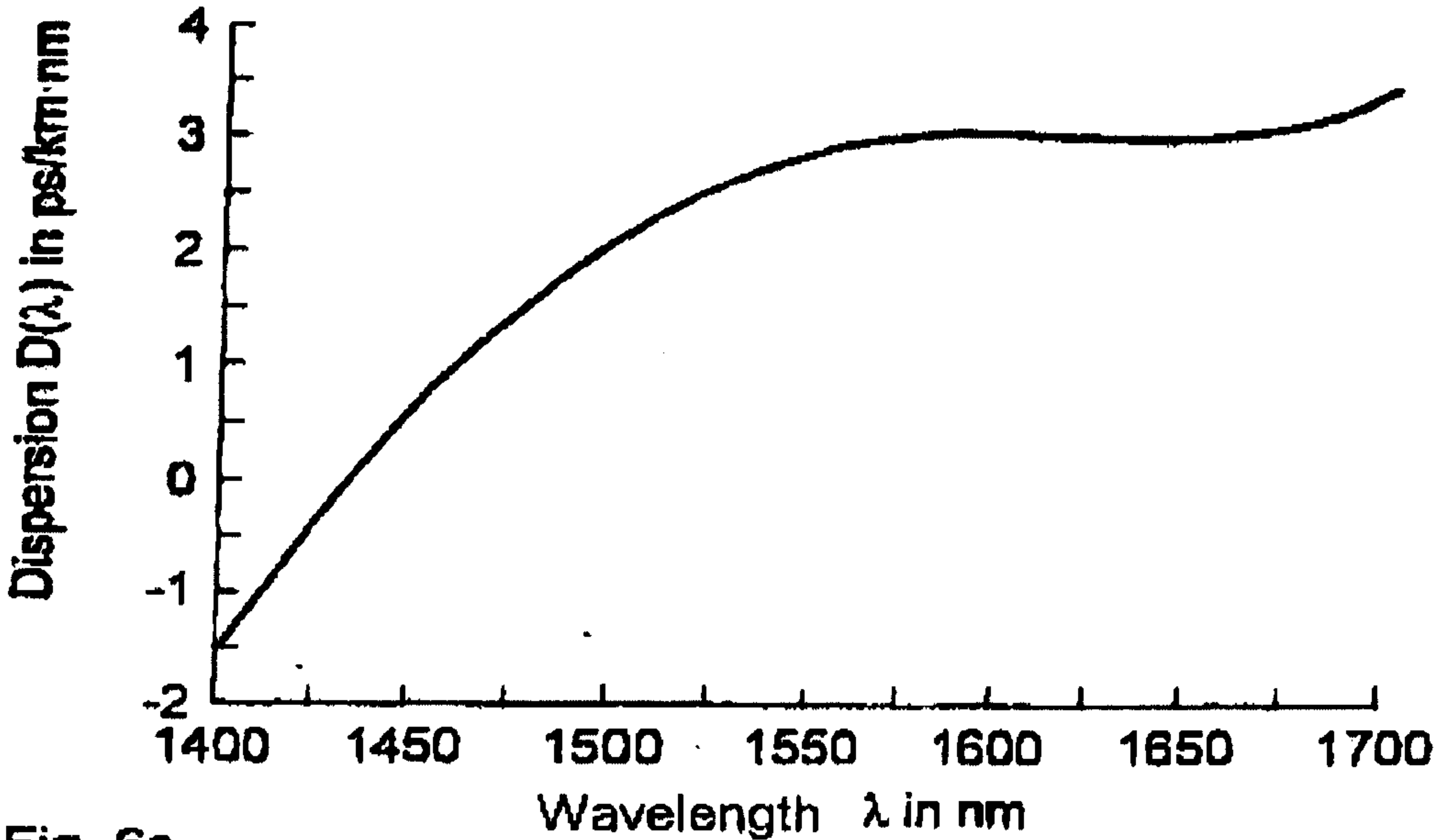
2Δ₁
2Δ₂
2Δ₃=0
0
2
4
r₁
6
8
10
r₂
12
14
a
Radius in µm

Fig. 5


Dispersion D(λ) in ps/km·nm
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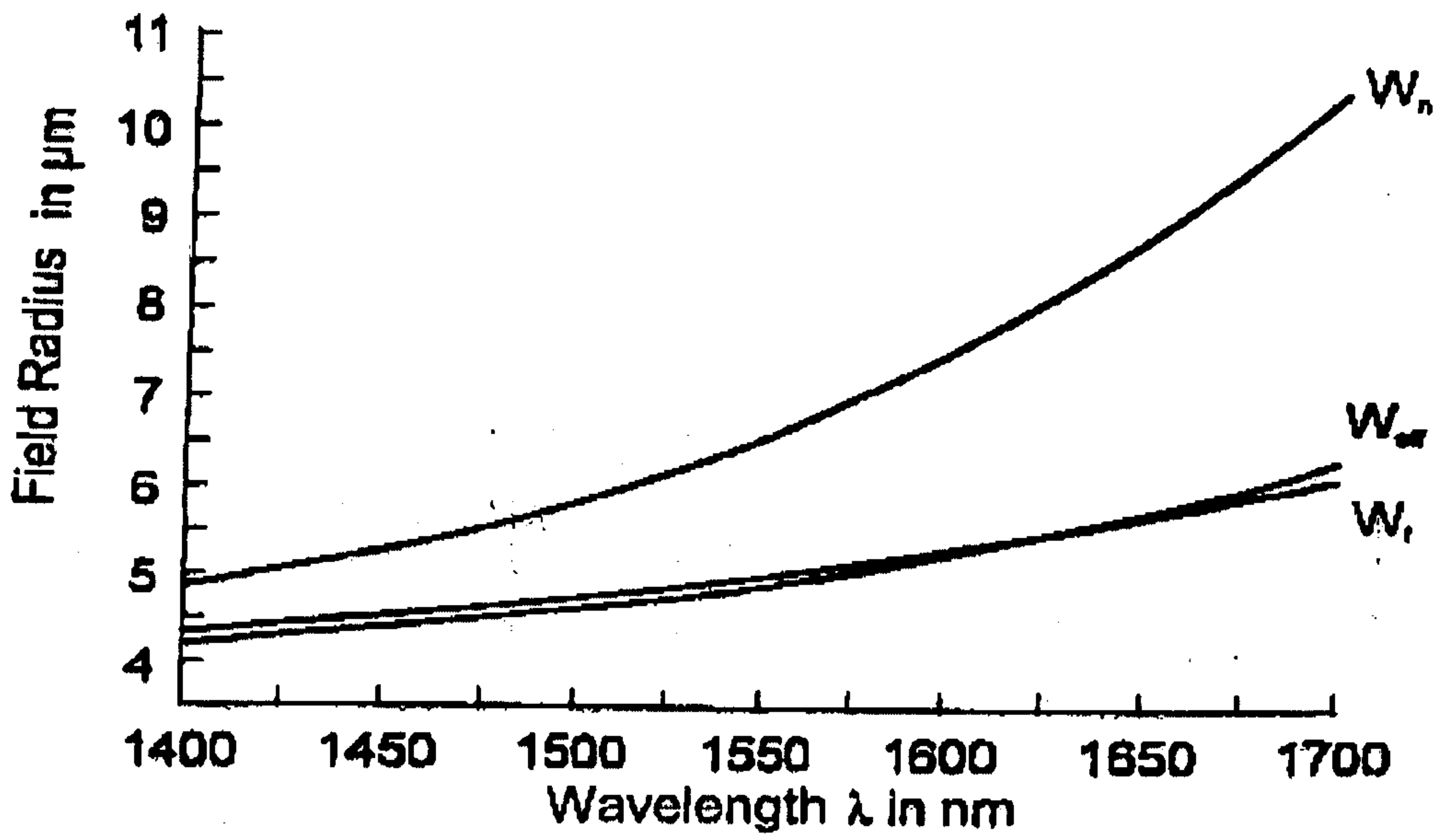
3
2
1
0
-1
-2
1400
1450
1500
1550
1600
1650
1700
Wavelength λ in nm

Fig. 6a


11
10
9
8
7
6
5
4
Field Radius in µm
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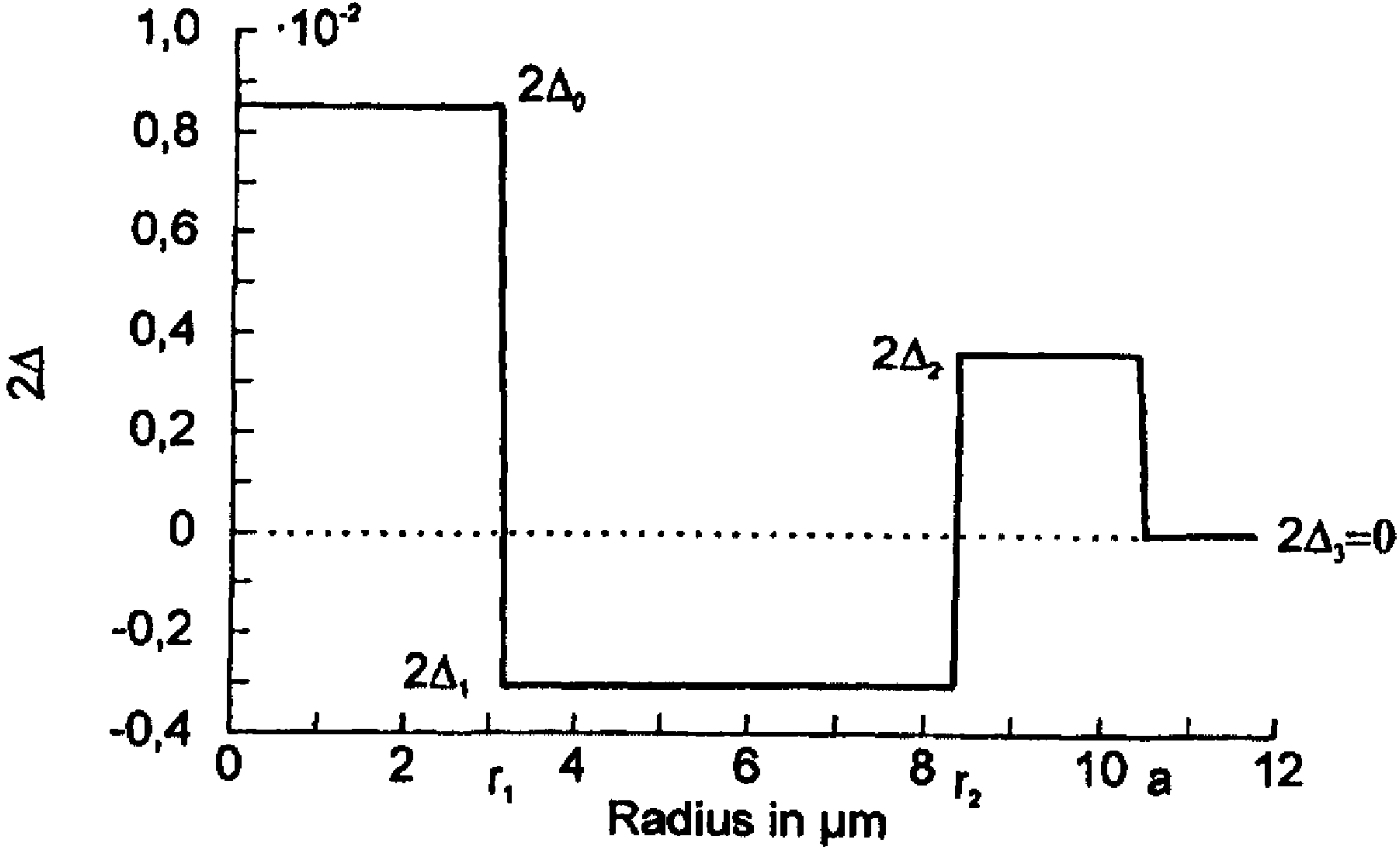
1450
1500
1550
1600
1650
1700
Wavelength λ in nm
W
W
W

Fig. 6b



1,0
·10⁻²
0,8
0,6
0,4
0,2
0
-0,2
-0,4
2Δ
2Δ0
2Δ1
2Δ2
2Δ3=0
0
2
r1
4
6
8
r2
10
a
12
Radius in µm